Fire & Smoke in the Earth System:

Evaluating the impact of fire aerosols on regional and global climate

Michael G. Tosca

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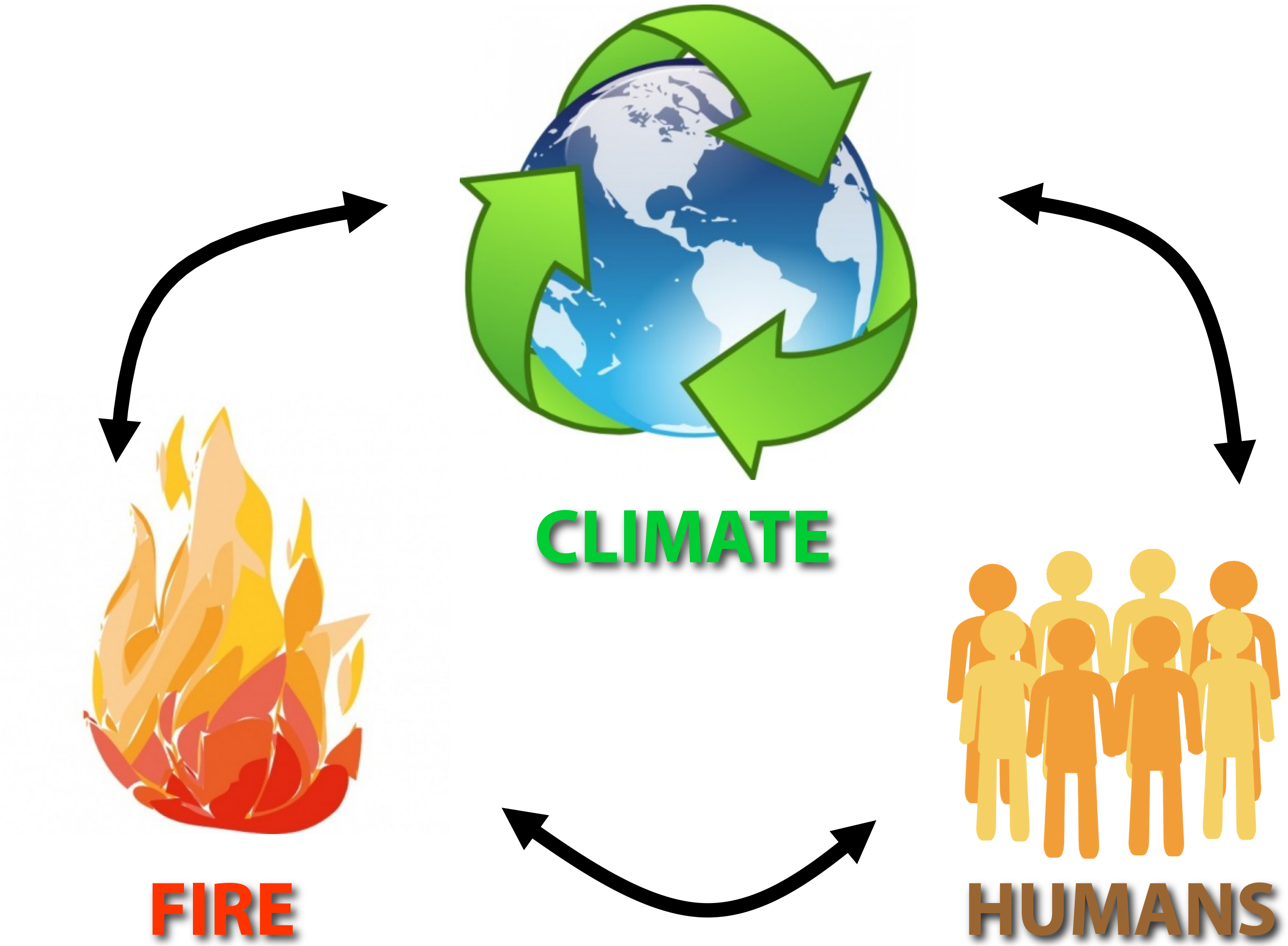
Presented to: NASA JPL || 1 March 2012

Fire, humans and climate



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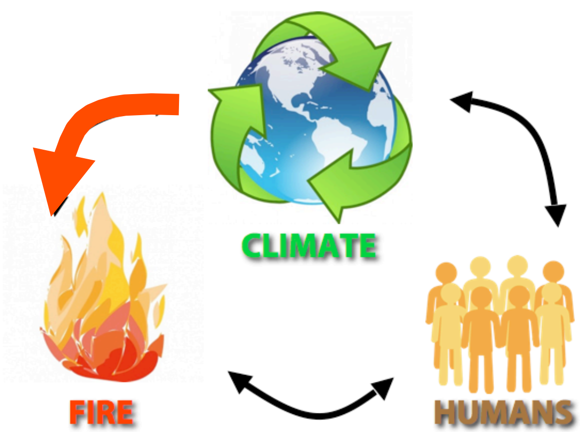
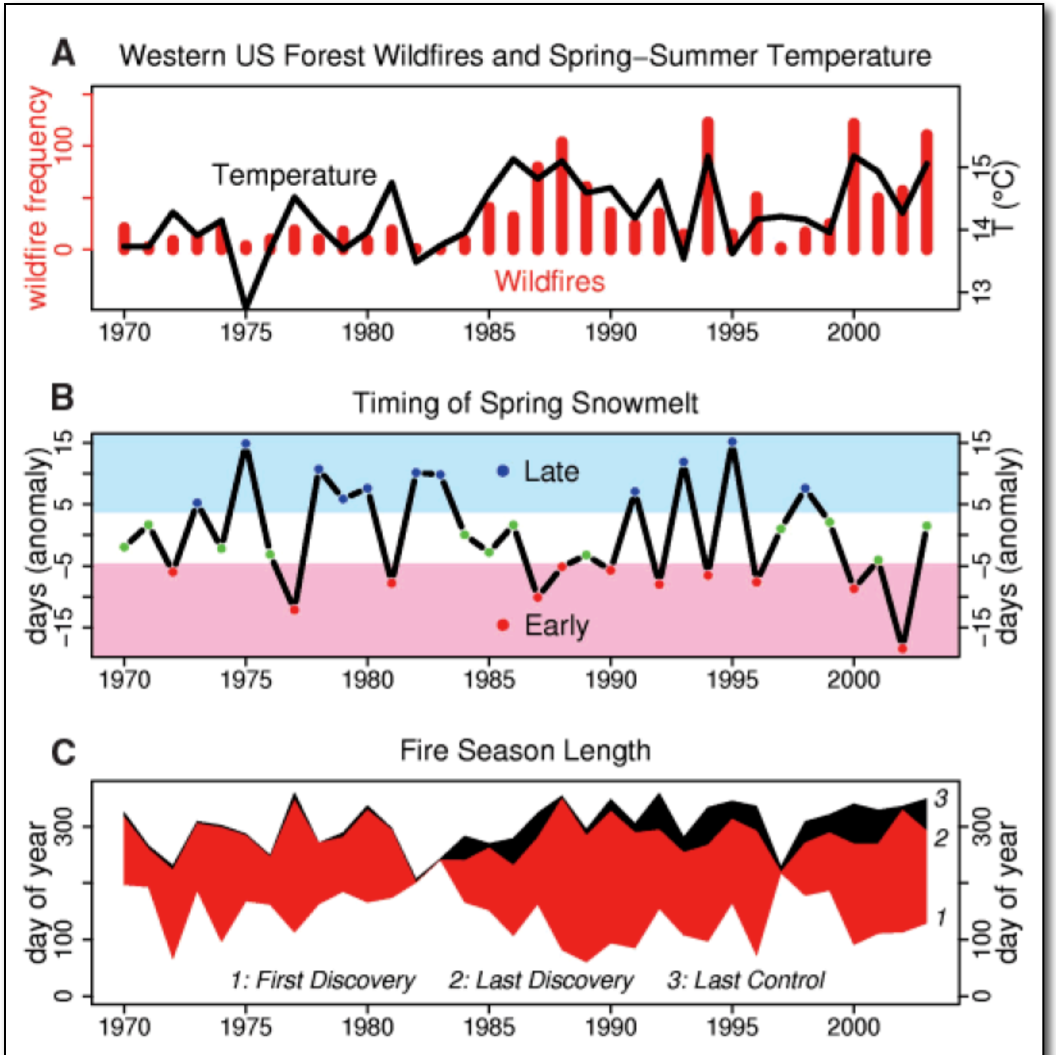
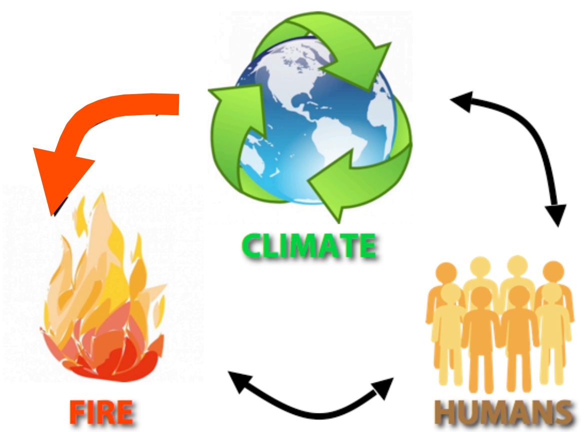
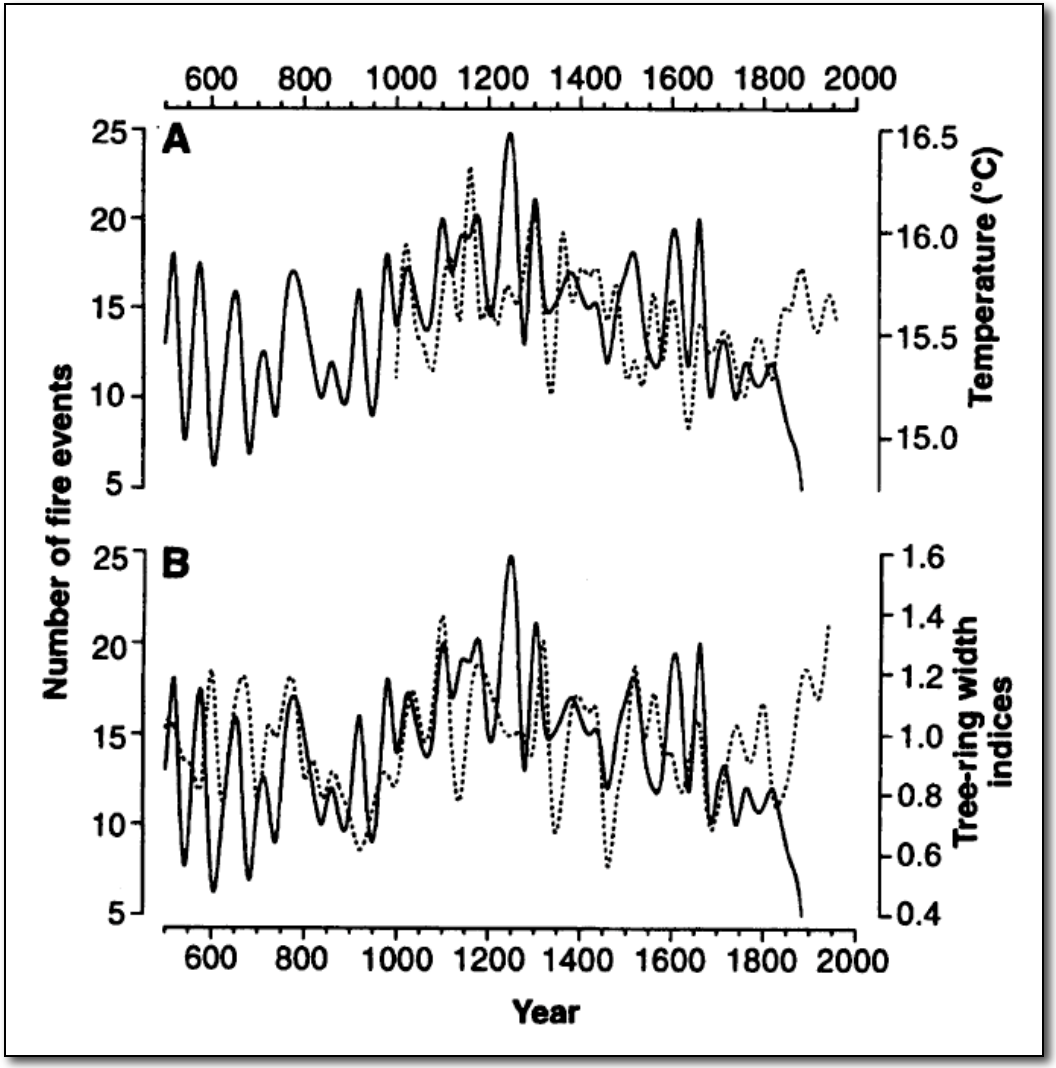




Westerling et al., 2006

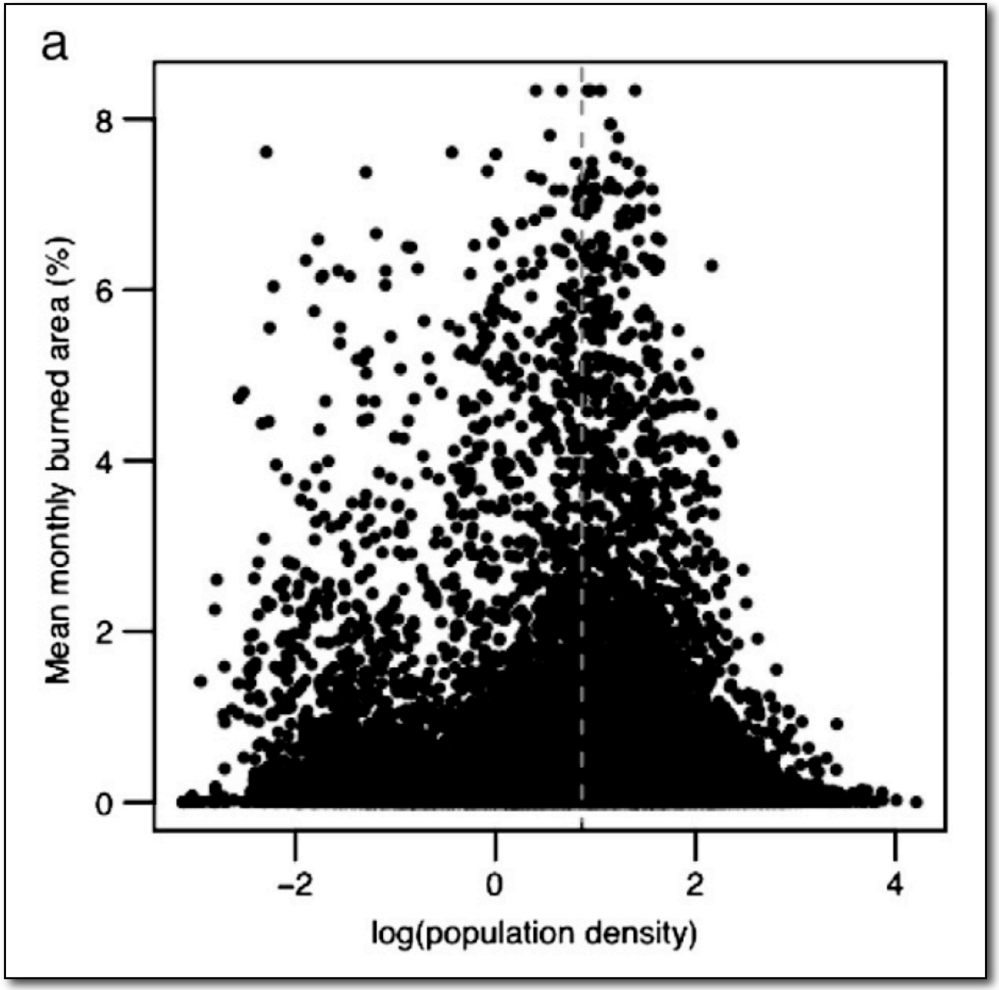
Fire, humans and climate



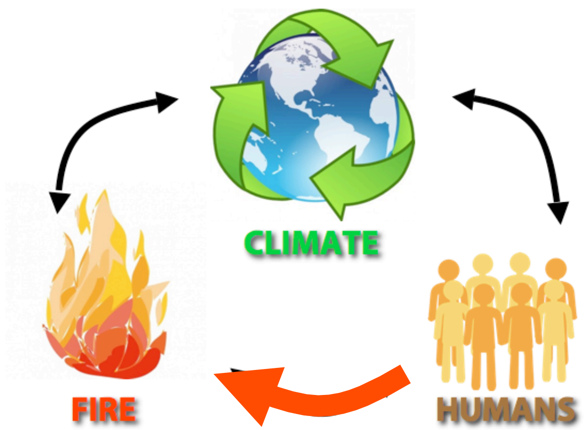


Swetnam et al., 1993

Fire, humans and climate



Aldersley et al., 2011



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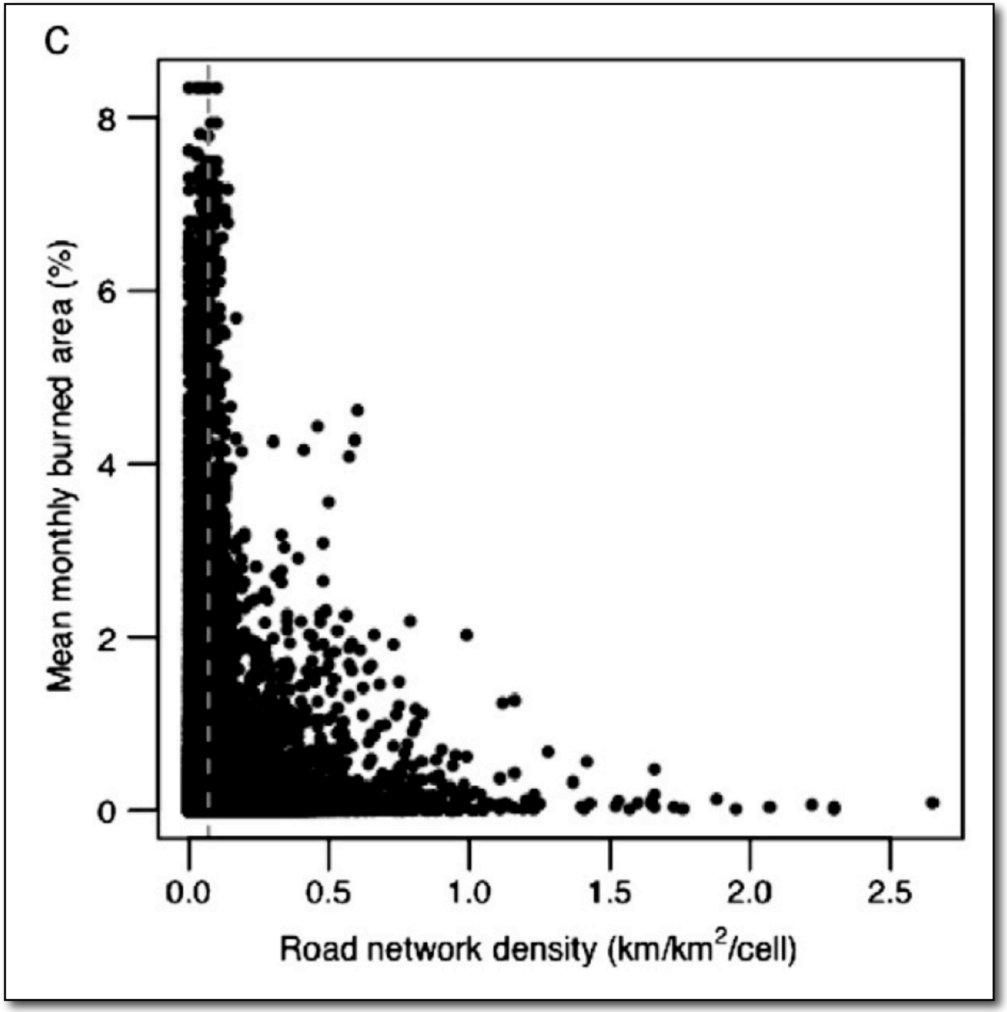

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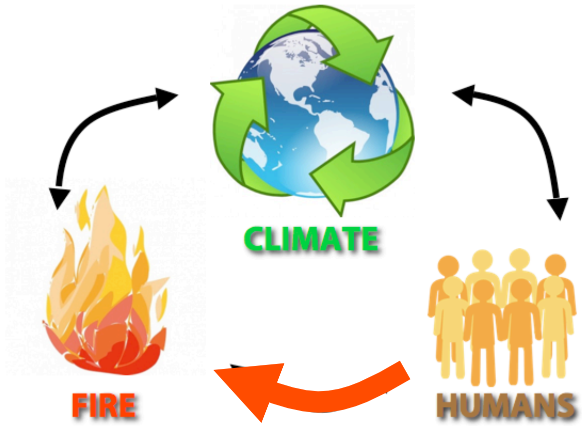
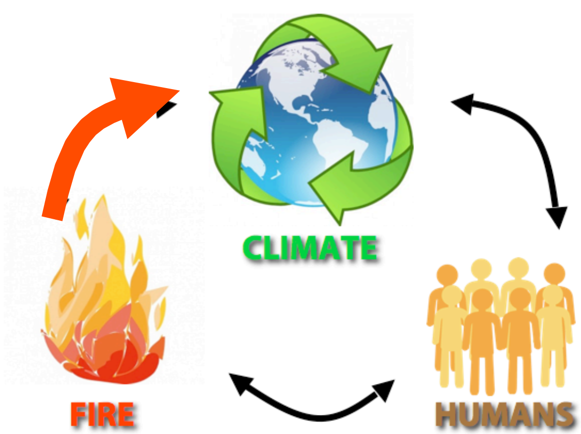
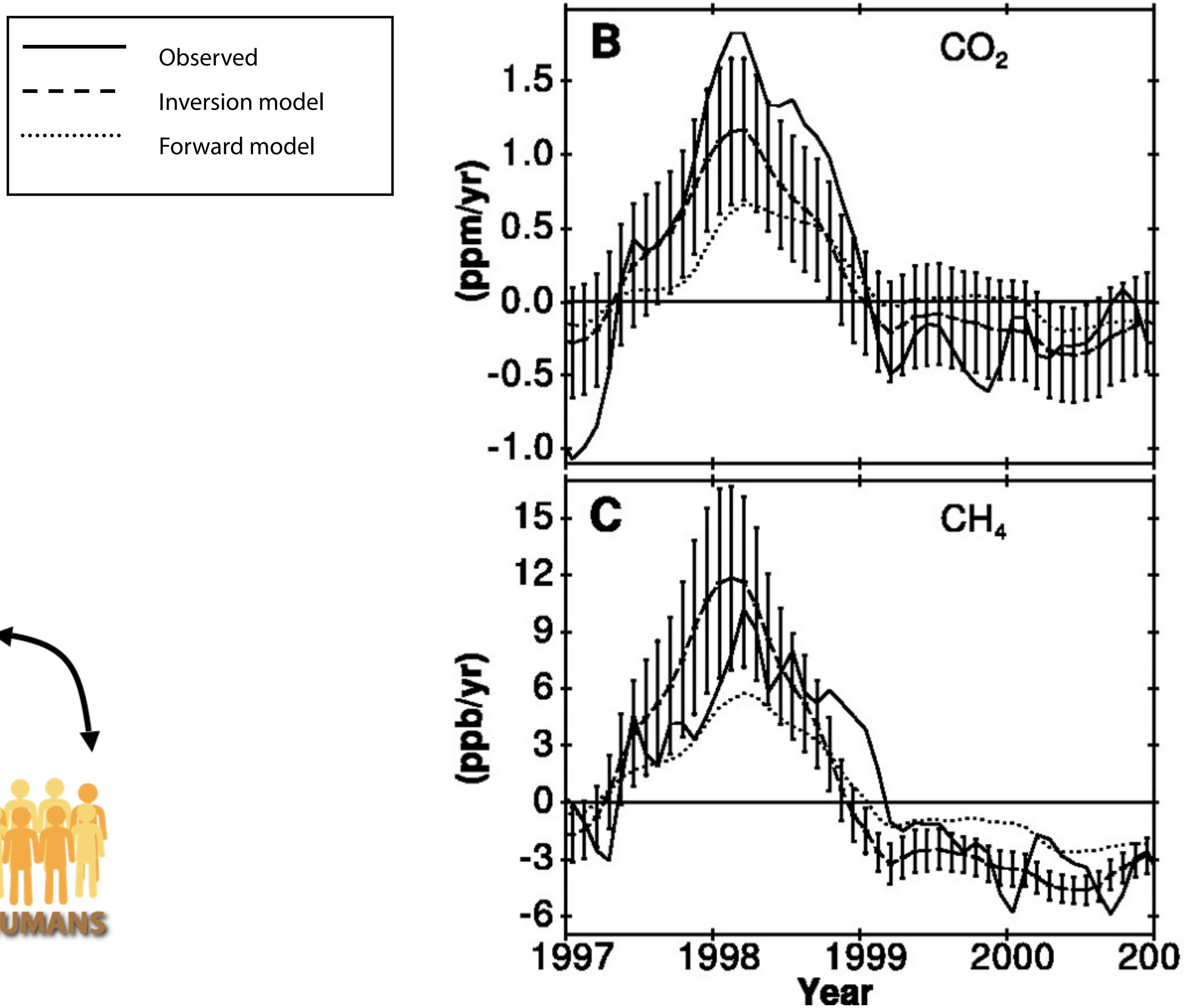


Fire impact on the carbon cycle



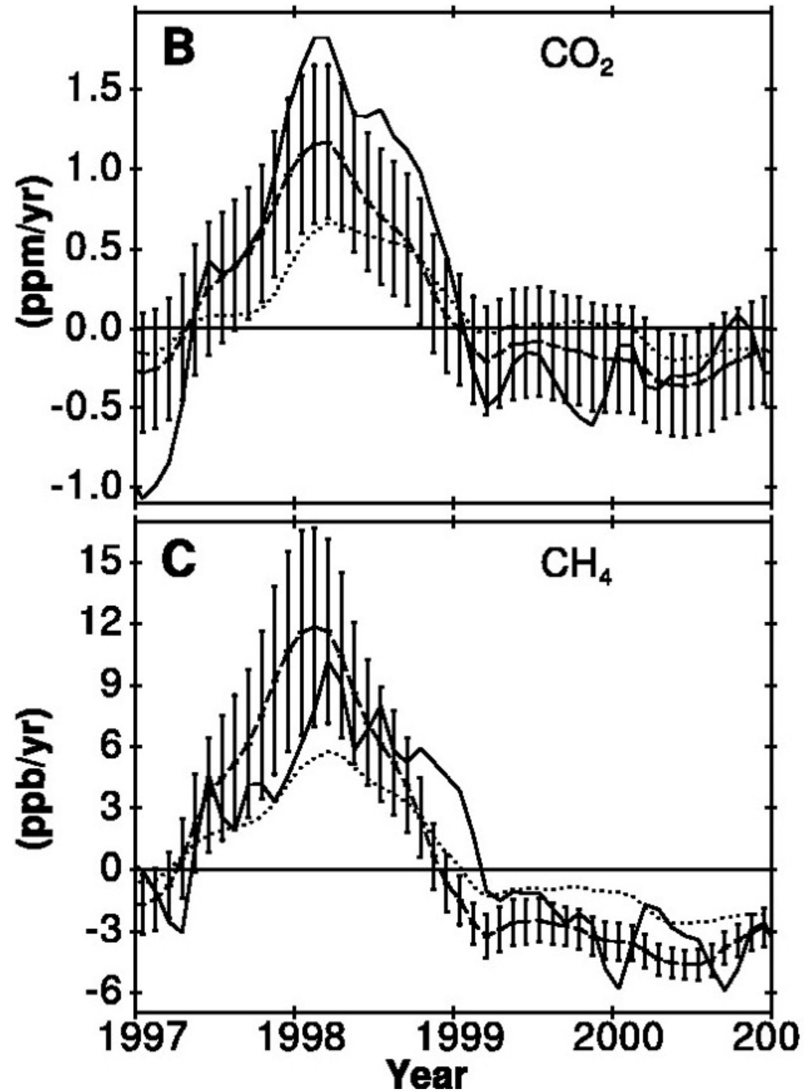
van der Werf et al., 2004



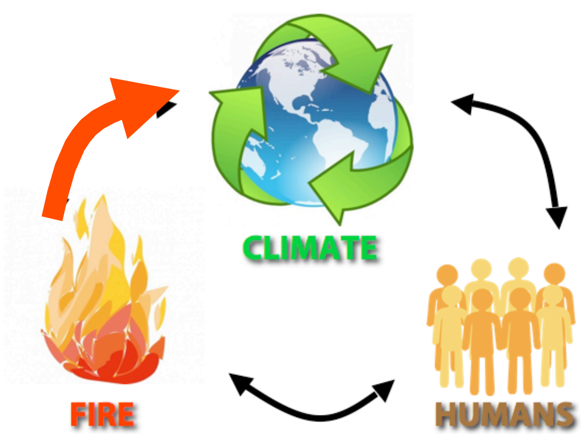
Fire impact on the carbon cycle

van der Werf et al., 2004

Observed
Inversion model
Forward model



During 1997-98, fire emissions explained ~2/3 of the observed CO_2 growth rate



Fire aerosol emissions - an introduction

Total global fire emissions: 2-4 Pg C yr^{-1} [1,2,3]

Deforestation emissions: 0.6-0.7 Pg C yr^{-1} [1]
(8% of fossil fuel emissions)

Smoke emissions: 50-100 Tg yr^{-1} [1,3,4]

5-10% of smoke emission mass is black carbon [5]

[1]van der Werf, et al., 2010 || [2]Wiedinmyer et al., 2011 || [3]Reid et al., 2009 || [4]Bauer and Menon, 2012 || [5]Reid et al., 2005

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Fires contribute ~30% of total particulate (smoke) and black carbon emissions worldwide. [6]

[6]Lamarque et al., 2010

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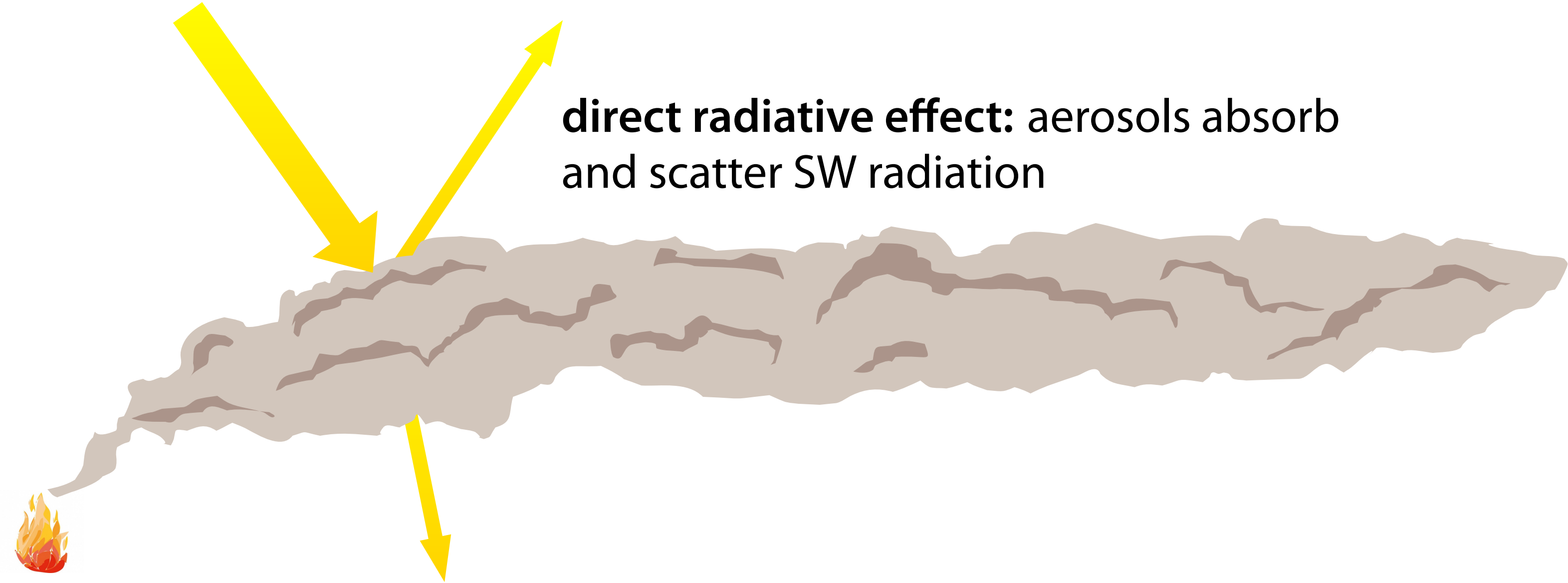
direct radiative effect: aerosols absorb and scatter SW radiation



Penner et al., 1994

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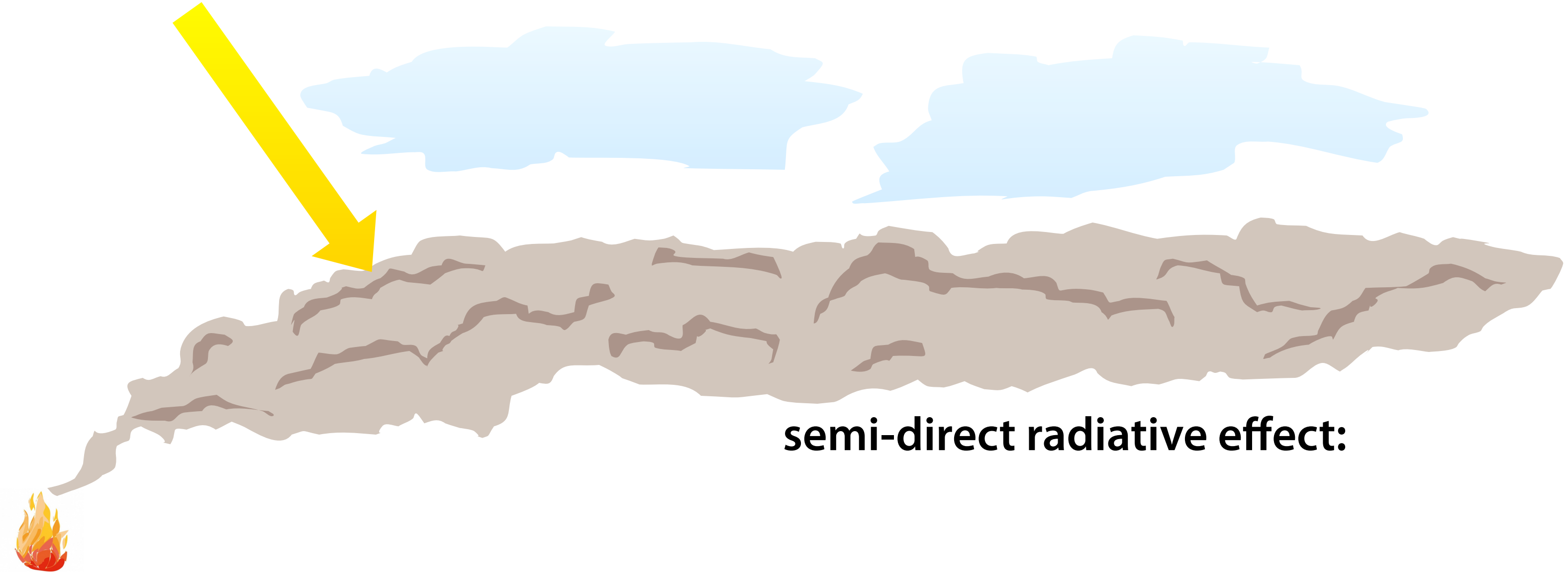

semi-direct radiative effect:

Ackerman et al., 2000

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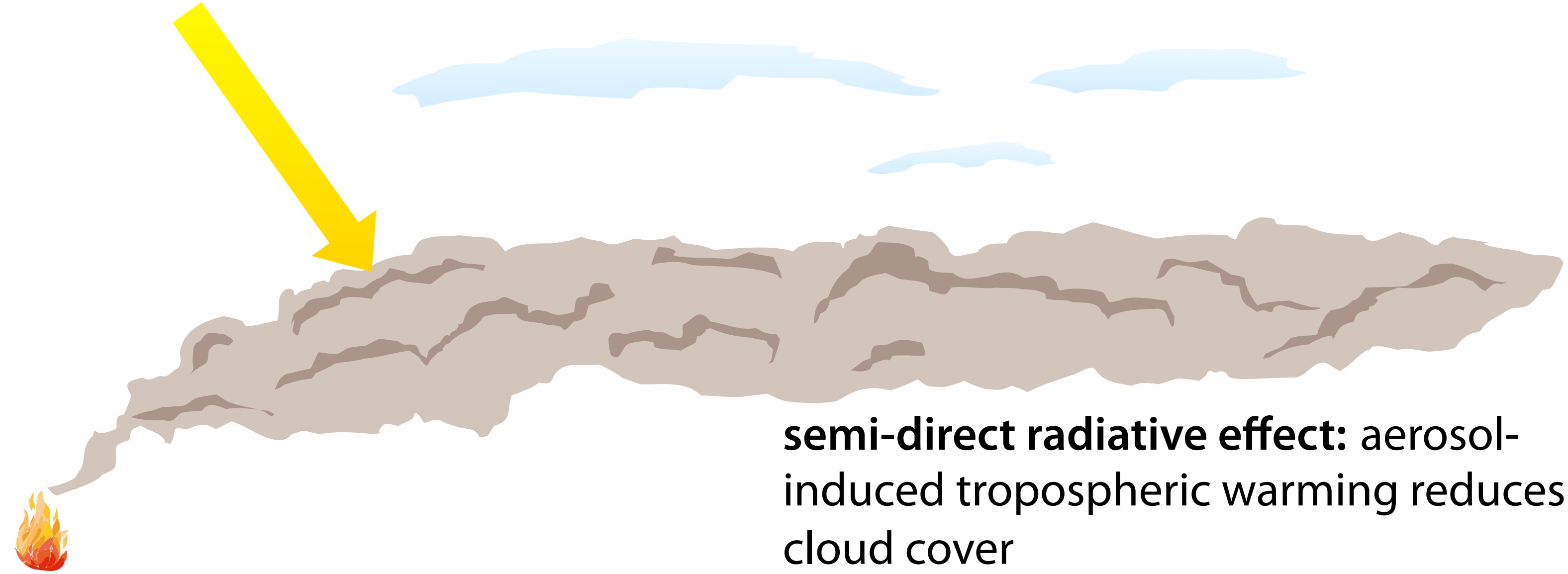

semi-direct radiative effect: aerosol-induced tropospheric warming reduces cloud cover

Ackerman et al., 2000

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Twomey, 1977

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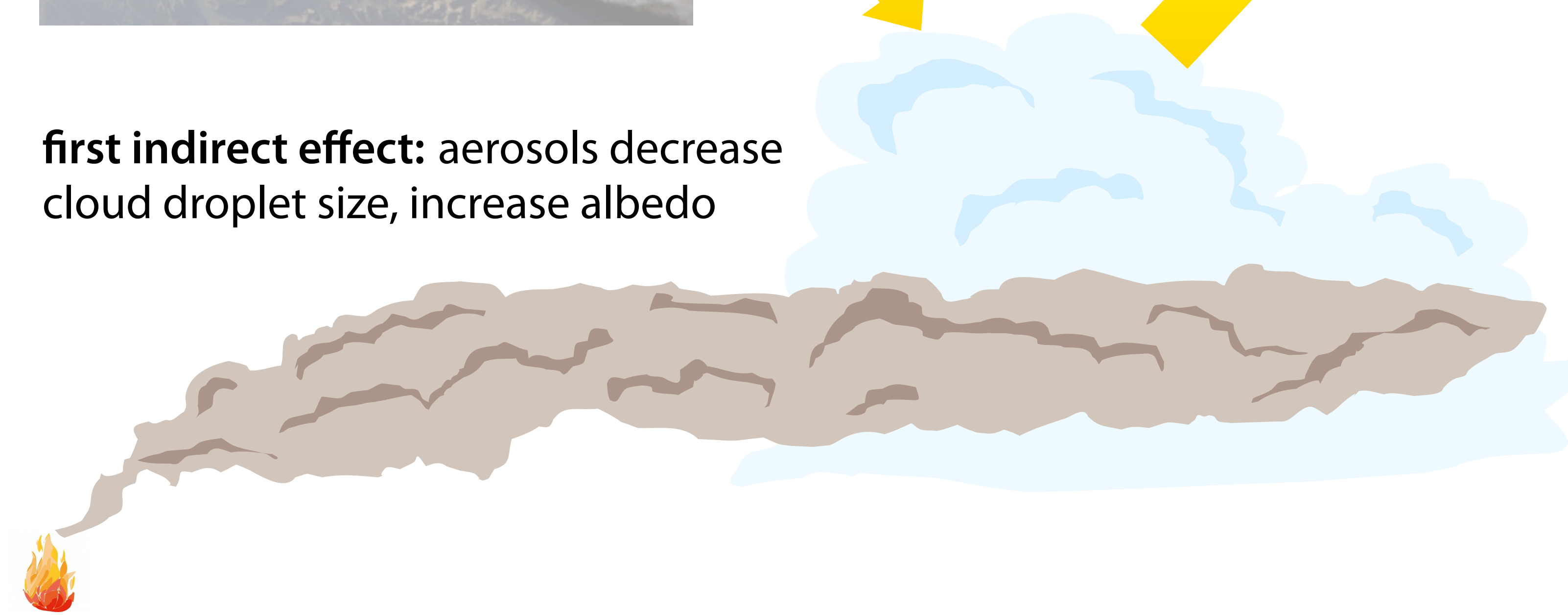

first indirect effect: aerosols decrease cloud droplet size, increase albedo

Twomey, 1977

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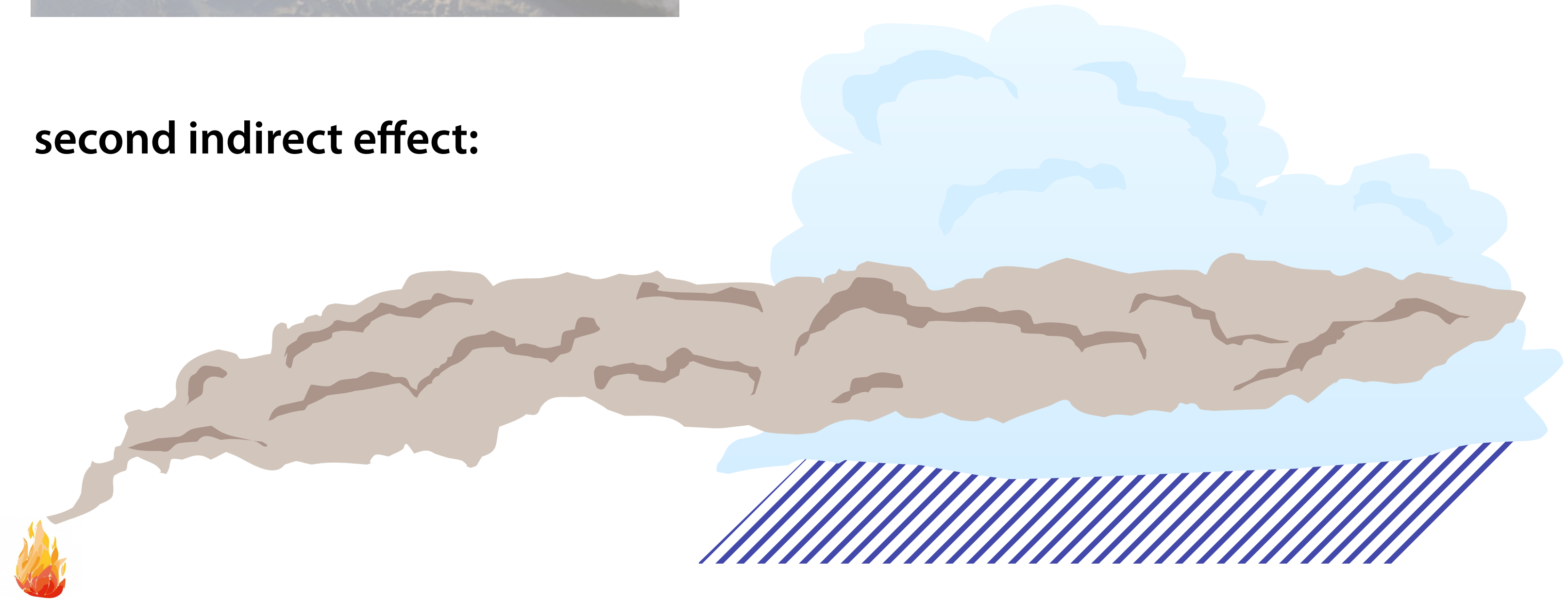
second indirect effect:



Albrecht, 1989

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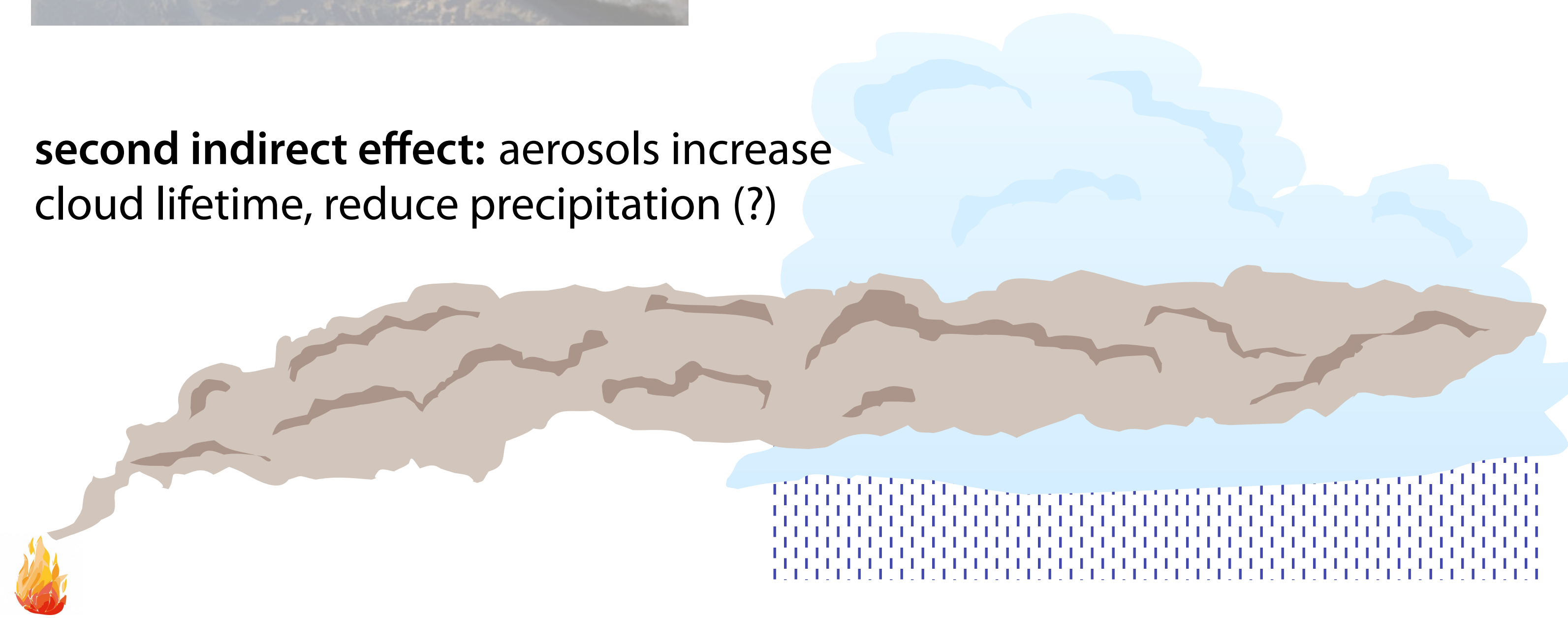
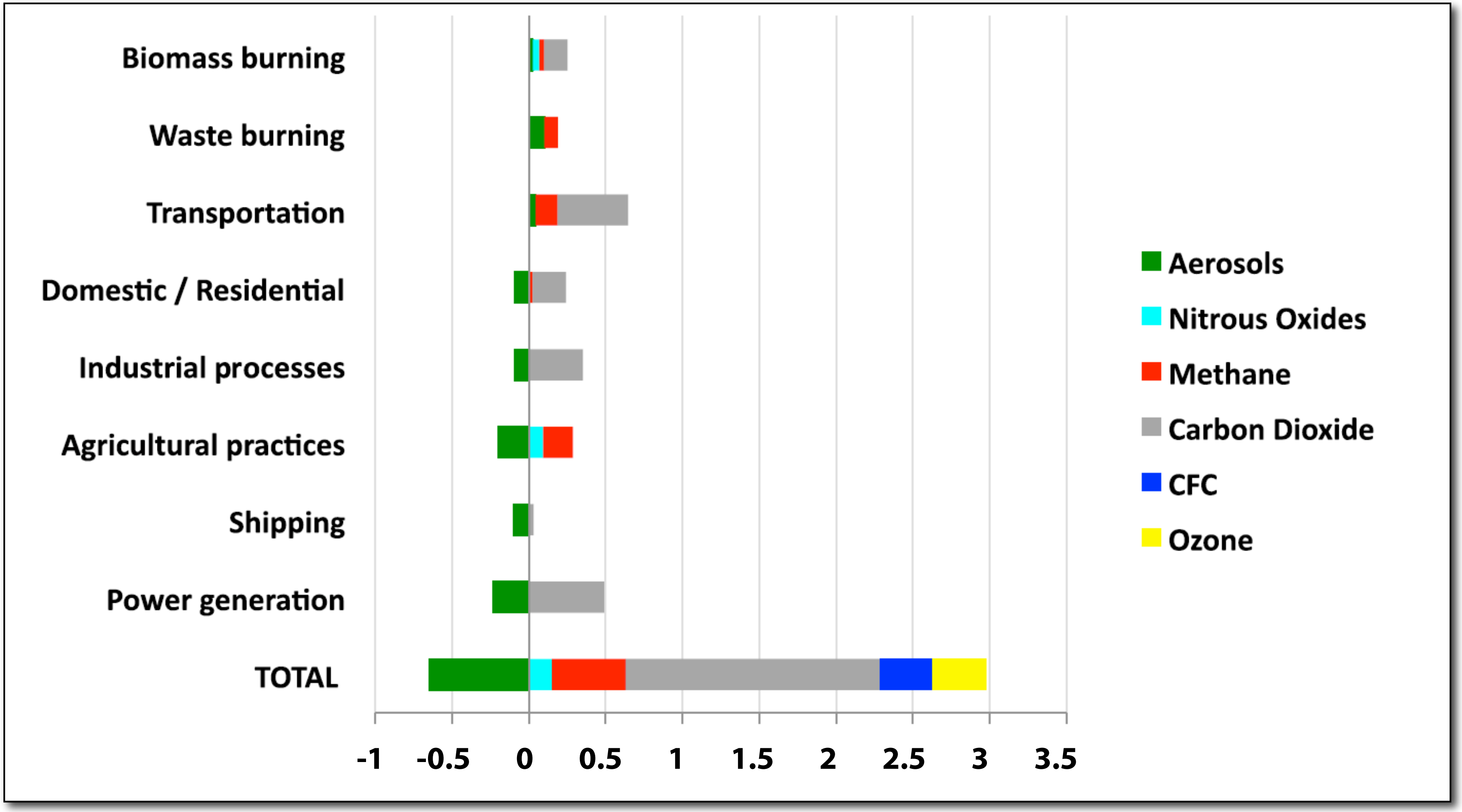


second indirect effect: aerosols increase cloud lifetime, reduce precipitation (?)

Albrecht, 1989

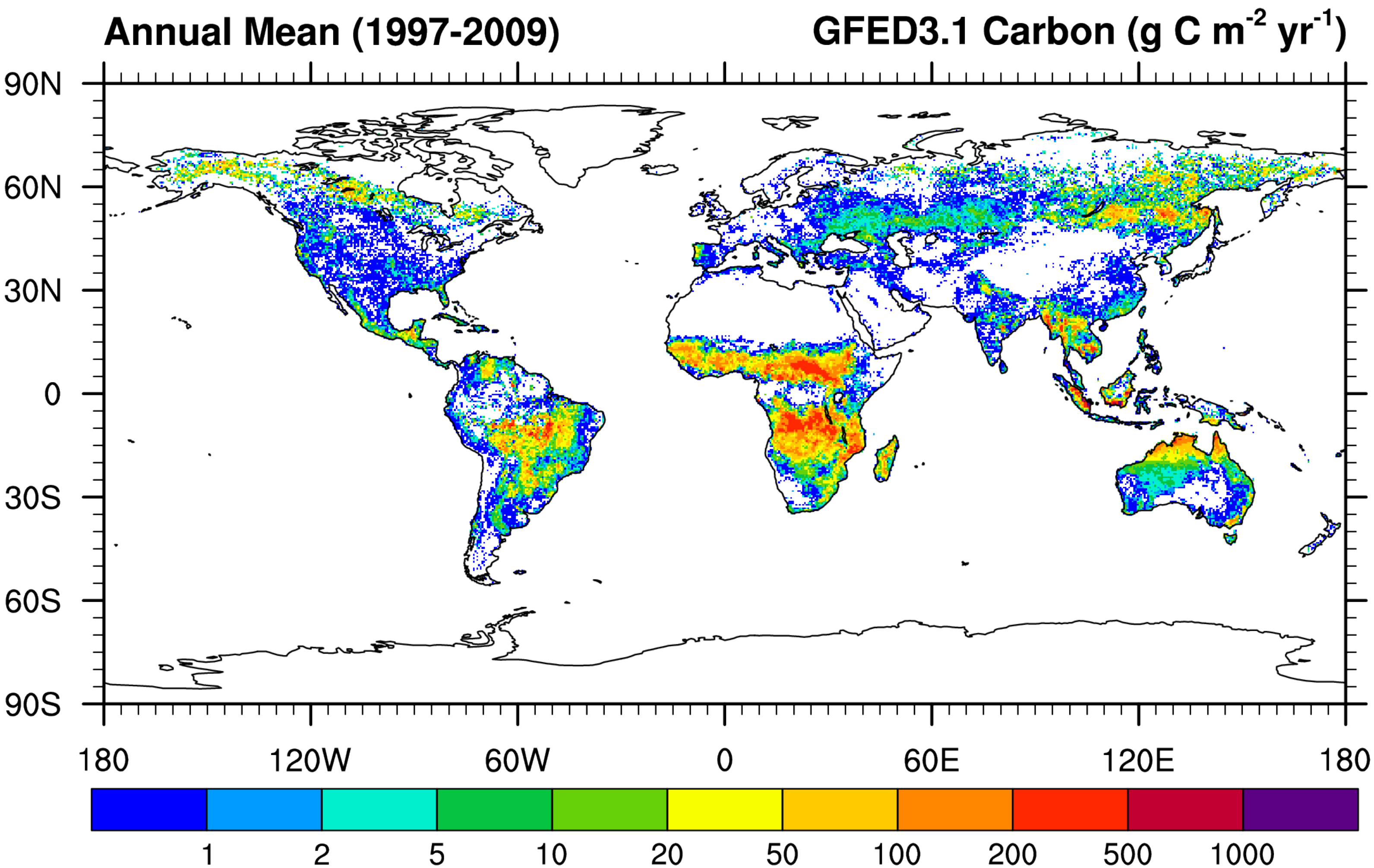
Global fire forcing (aerosols)



from: Bauer et al., 2012

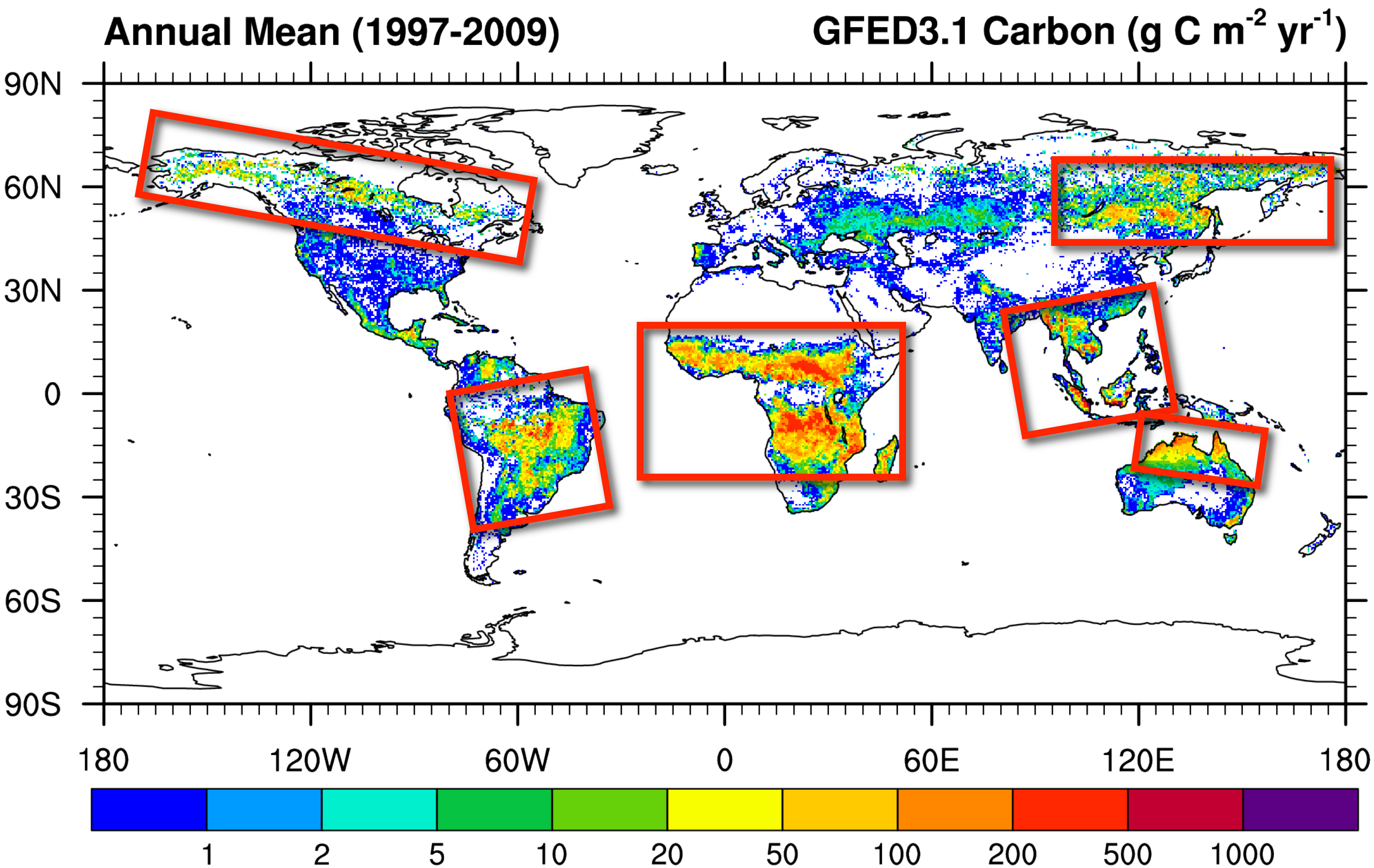
- ➢ Global radiative forcing (RF) from *all* aerosols is **–0.5 W m^{-2}**
- ➢ RF from *fire* aerosols is **+0.005 W m^{-2}**

Global distribution of fire emissions



from: van der Werf et al., 2010

High burning regions



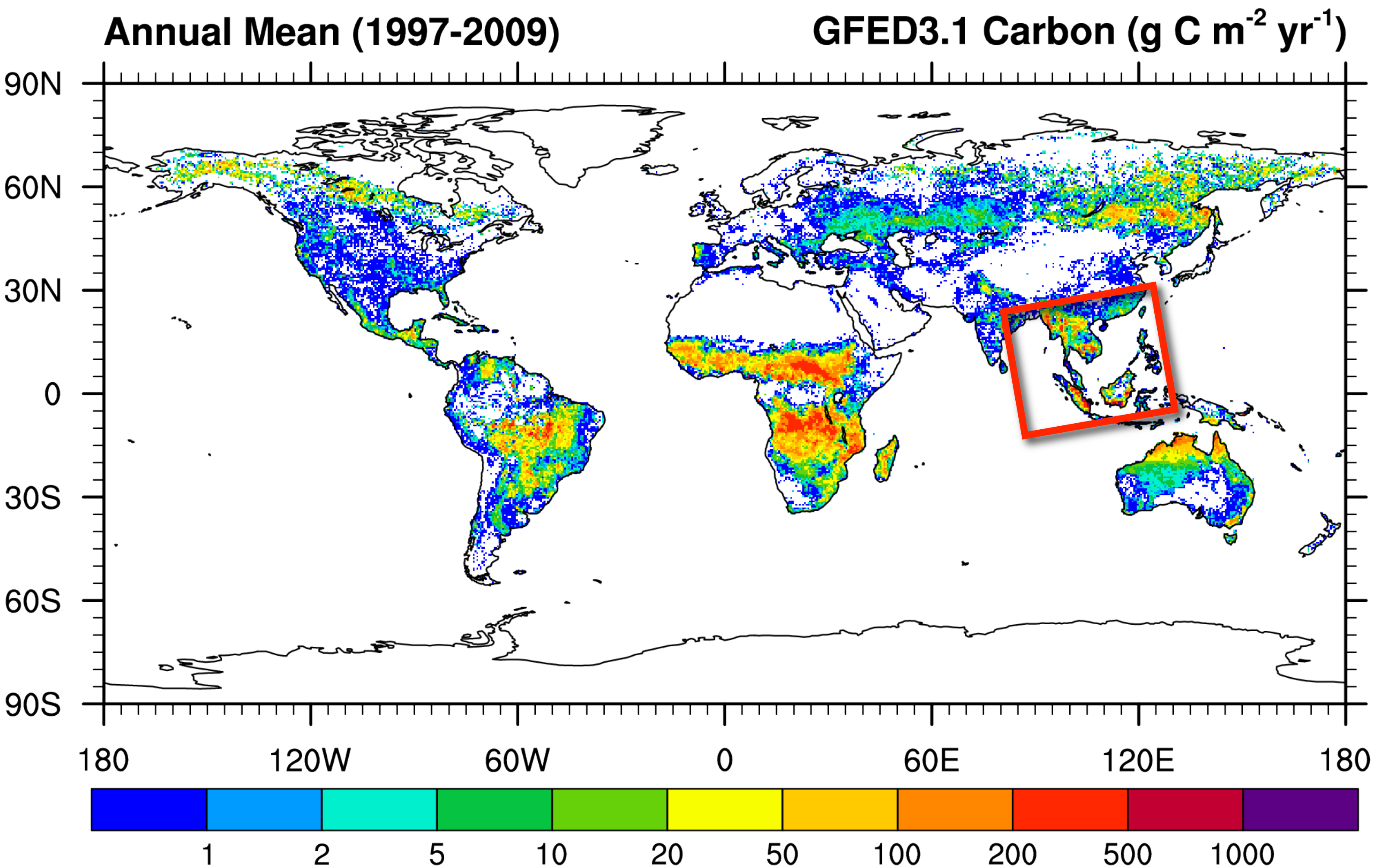
Hypotheses

1. **Fires in tropical Asian peat forests generally smolder and are injected within the boundary layer.**

2. **Climate impacts of fire aerosols during El Niño drought provide evidence of a positive feedback.**

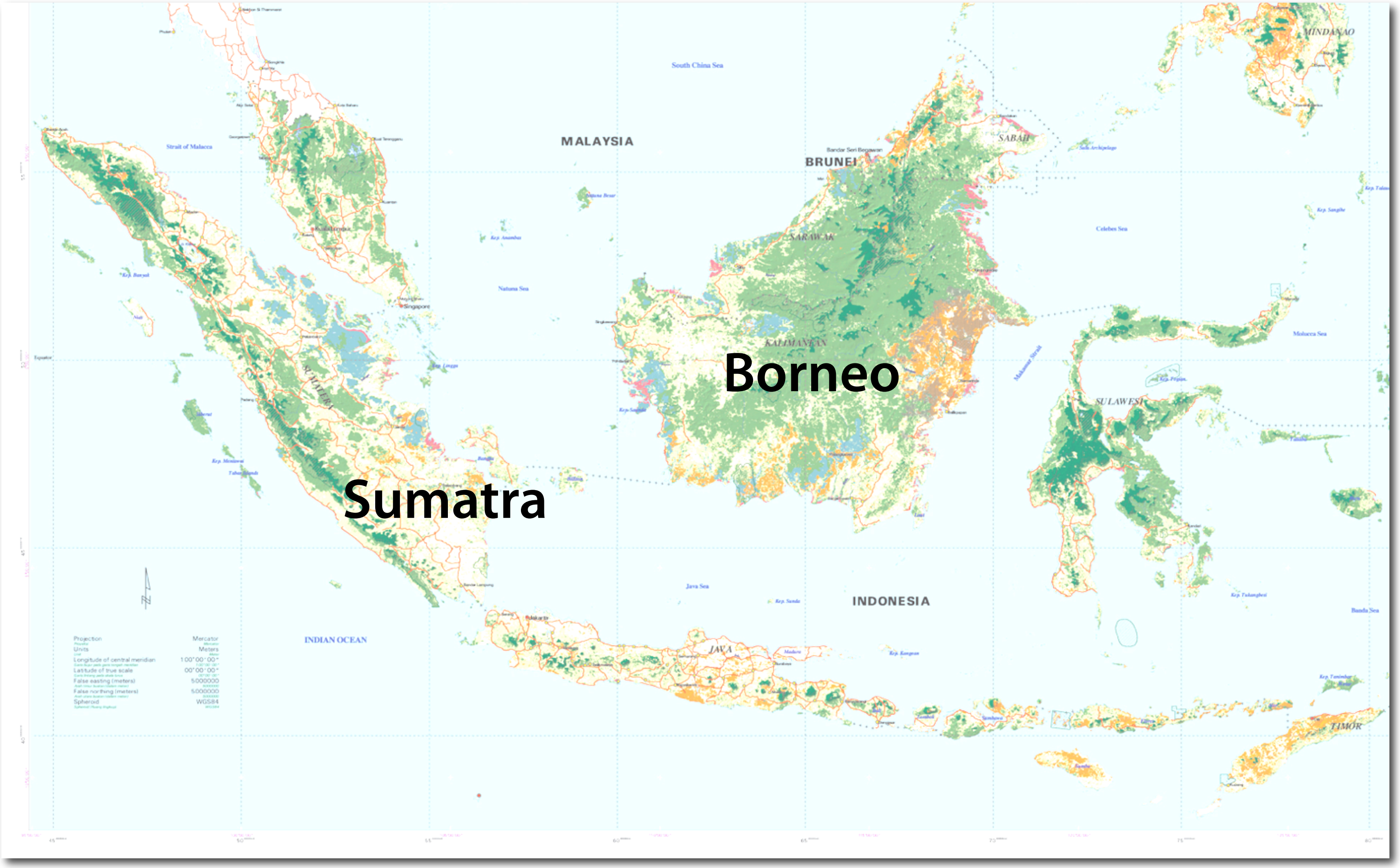
3. **Global climate is strongly influenced by the radiative and microphysical effects of fire aerosols; tropical forests near source regions are particularly vulnerable to climate changes.**

southeast + equatorial Asia

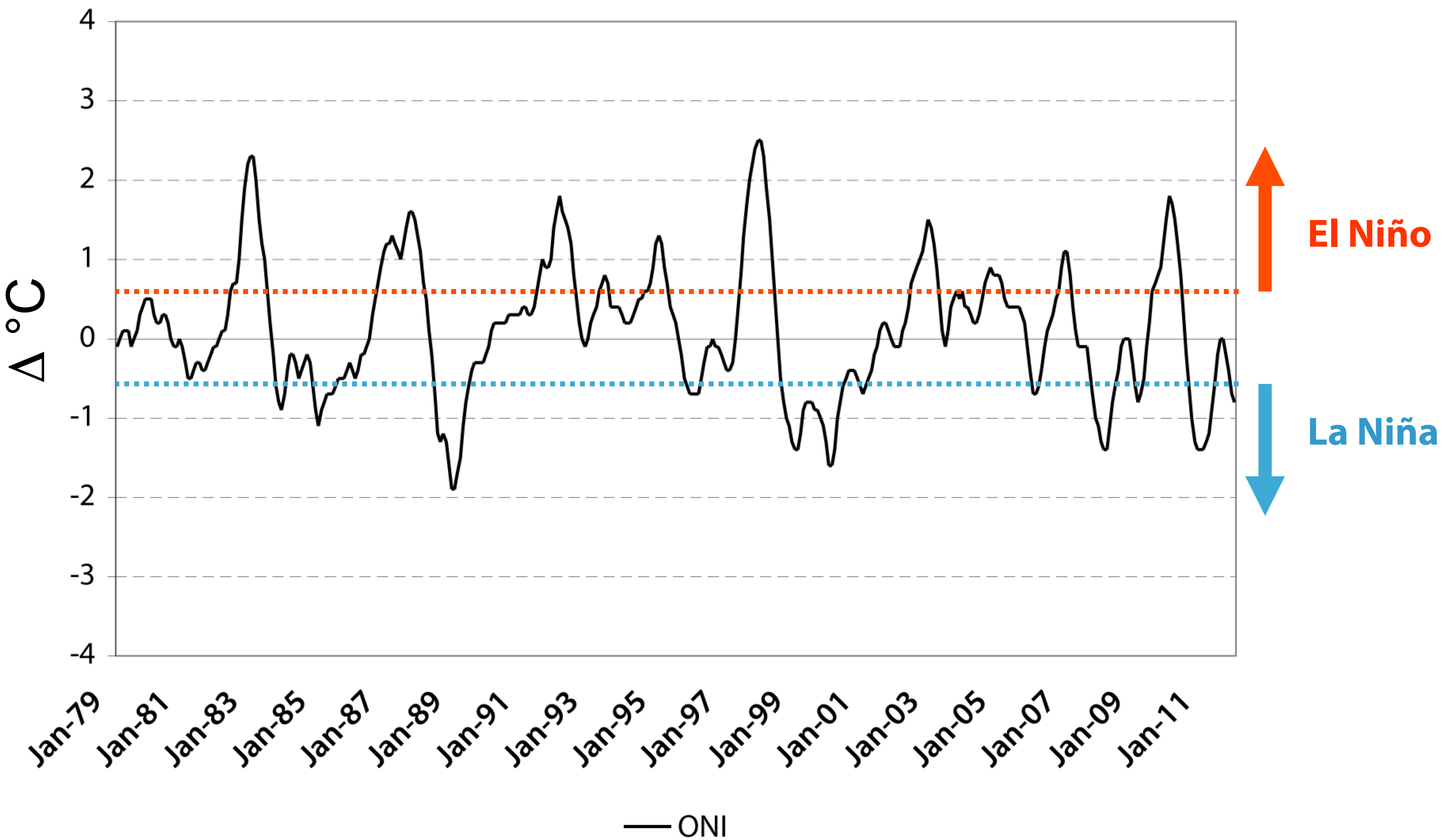


➤ Burning in equatorial Asia (Indonesia, Malaysia, Papau New Guinea)

Map of equatorial Asia



Link between ENSO and fire



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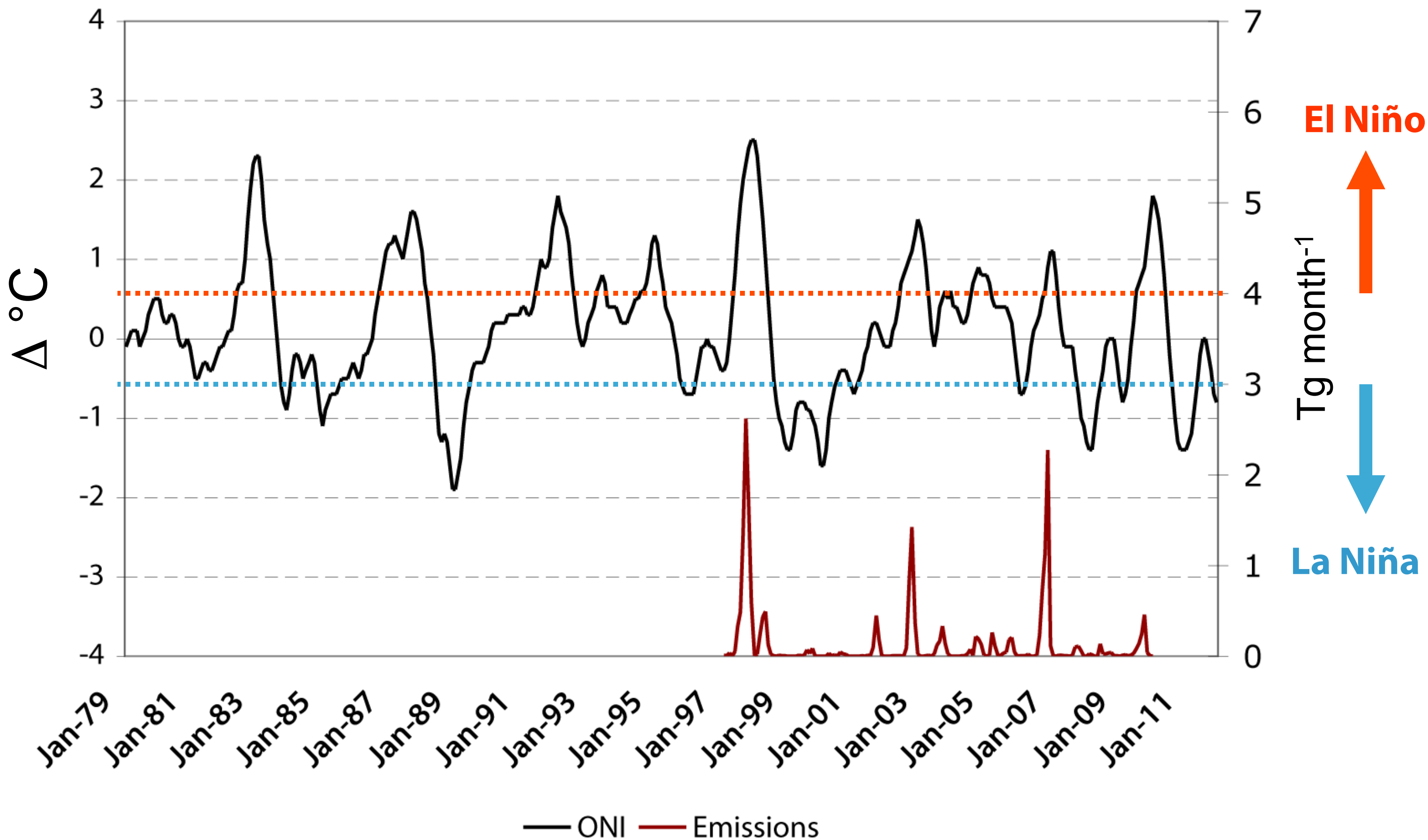

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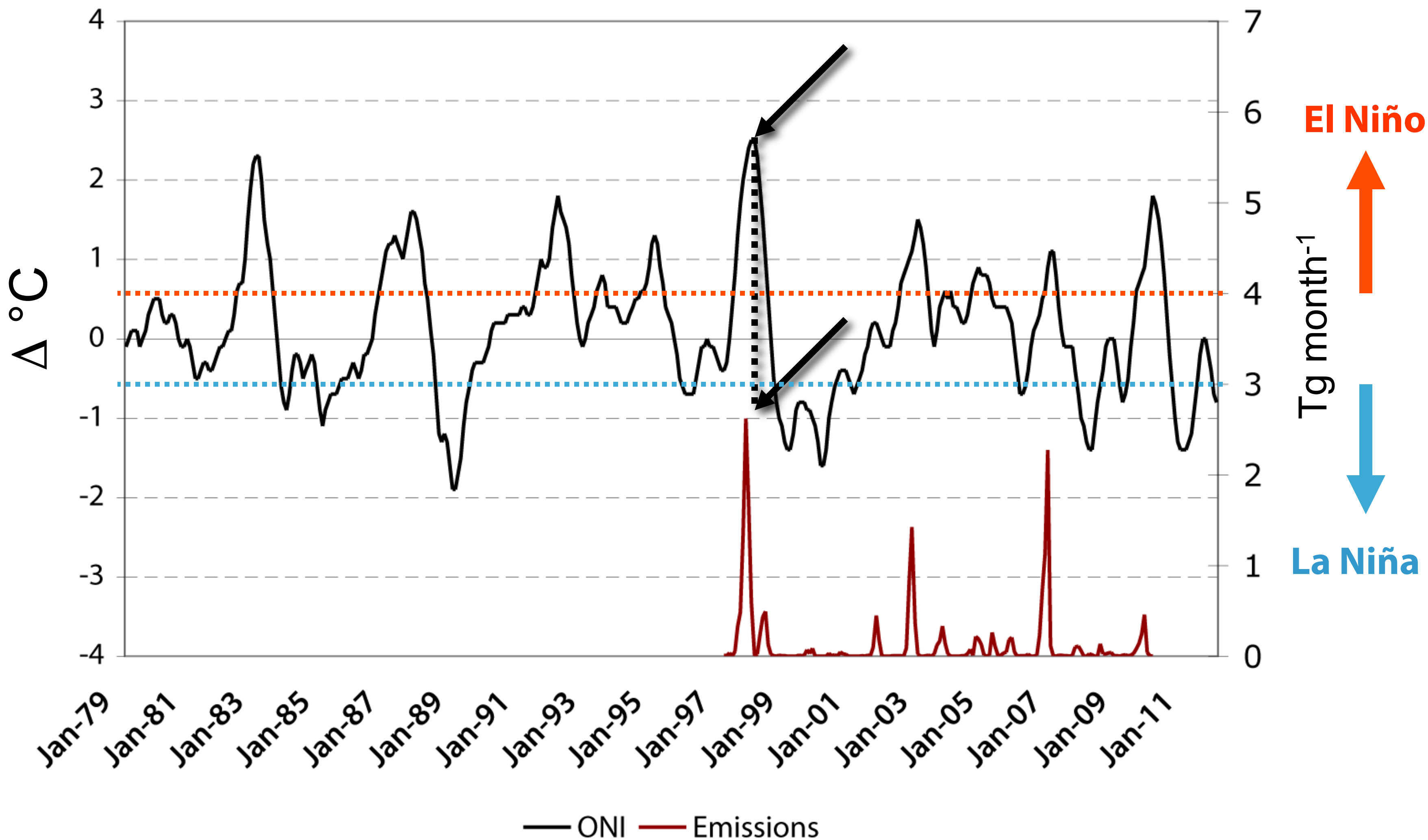

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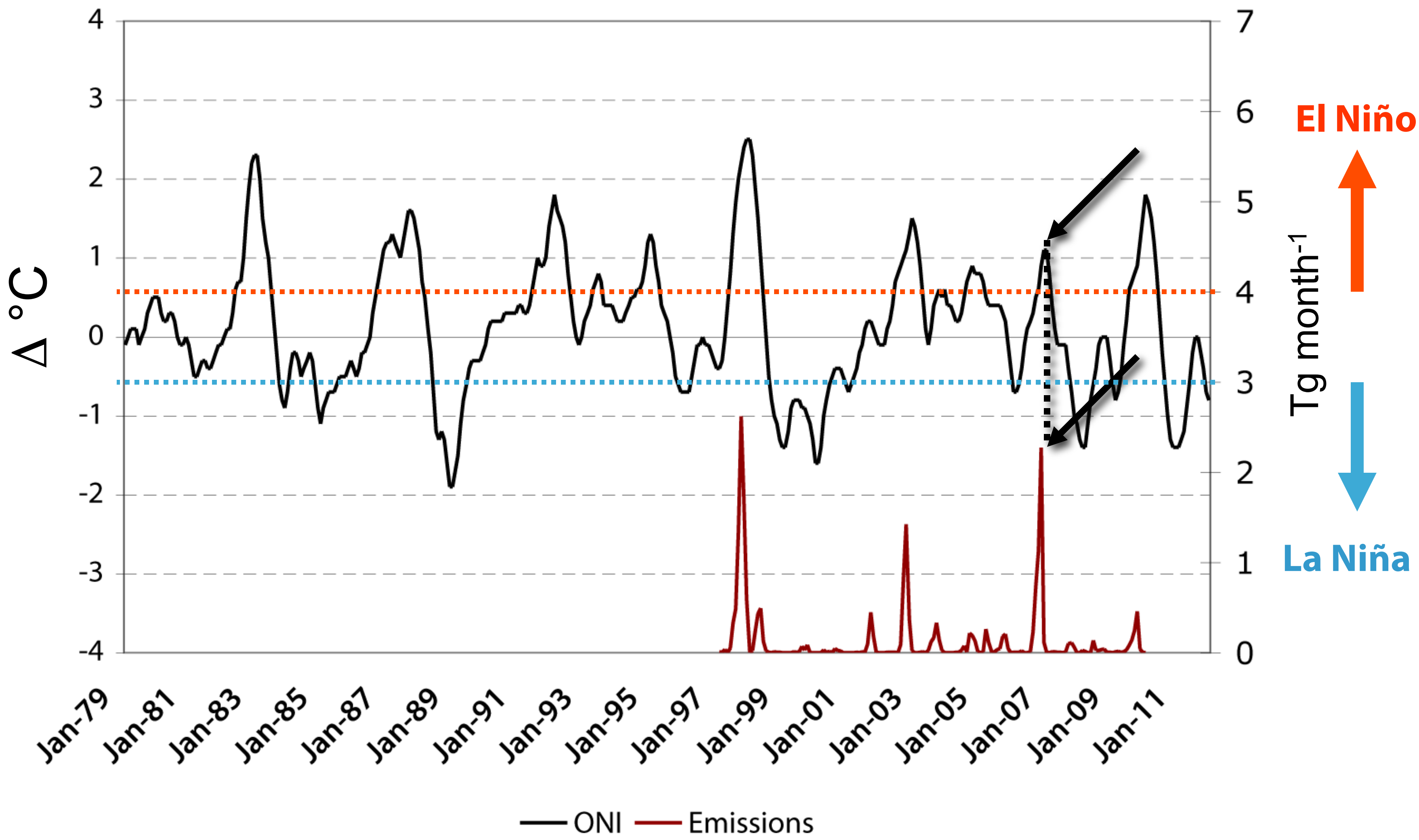
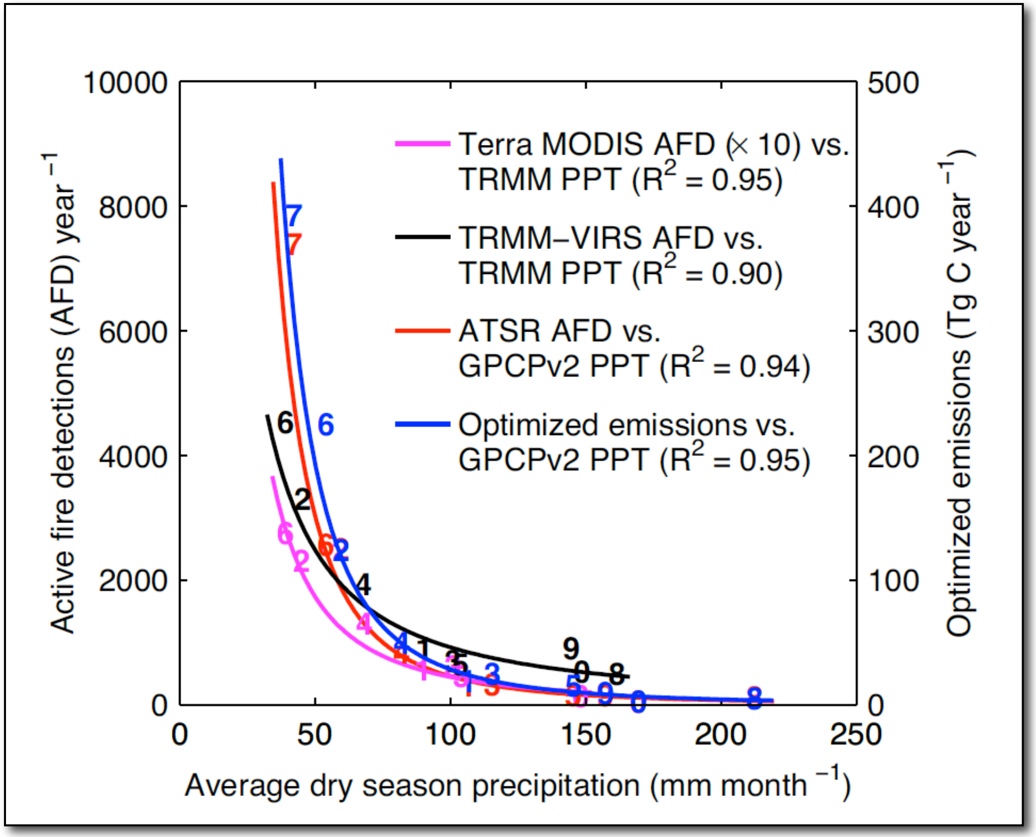


Fire during El Niño driven by low precipitation

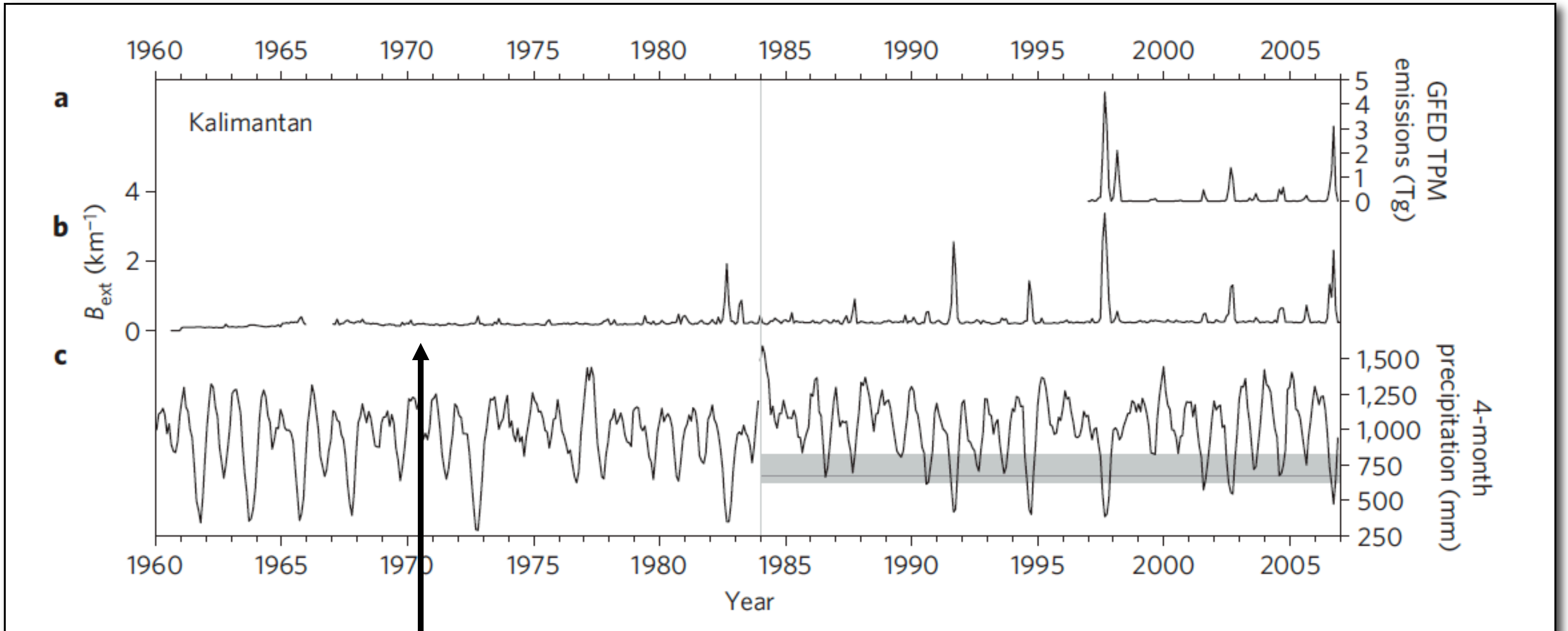


from: van der Werf et al., 2008

- ➢ Exponential relationship; almost piecewise w/ critical value ~100 mm month^{-1}
- ➢ High burning in 1997 and 2006 associated with average dry season precipitation ~50 mm month^{-1}
- ➢ Very low burning in 1998, 1999, 2000 associated with average dry season precipitation >150 mm month^{-1}

Fire during El Niño driven by low precipitation

➢ Fairly recent phenomenon, especially on Borneo, associated with changing migration/settlement patterns

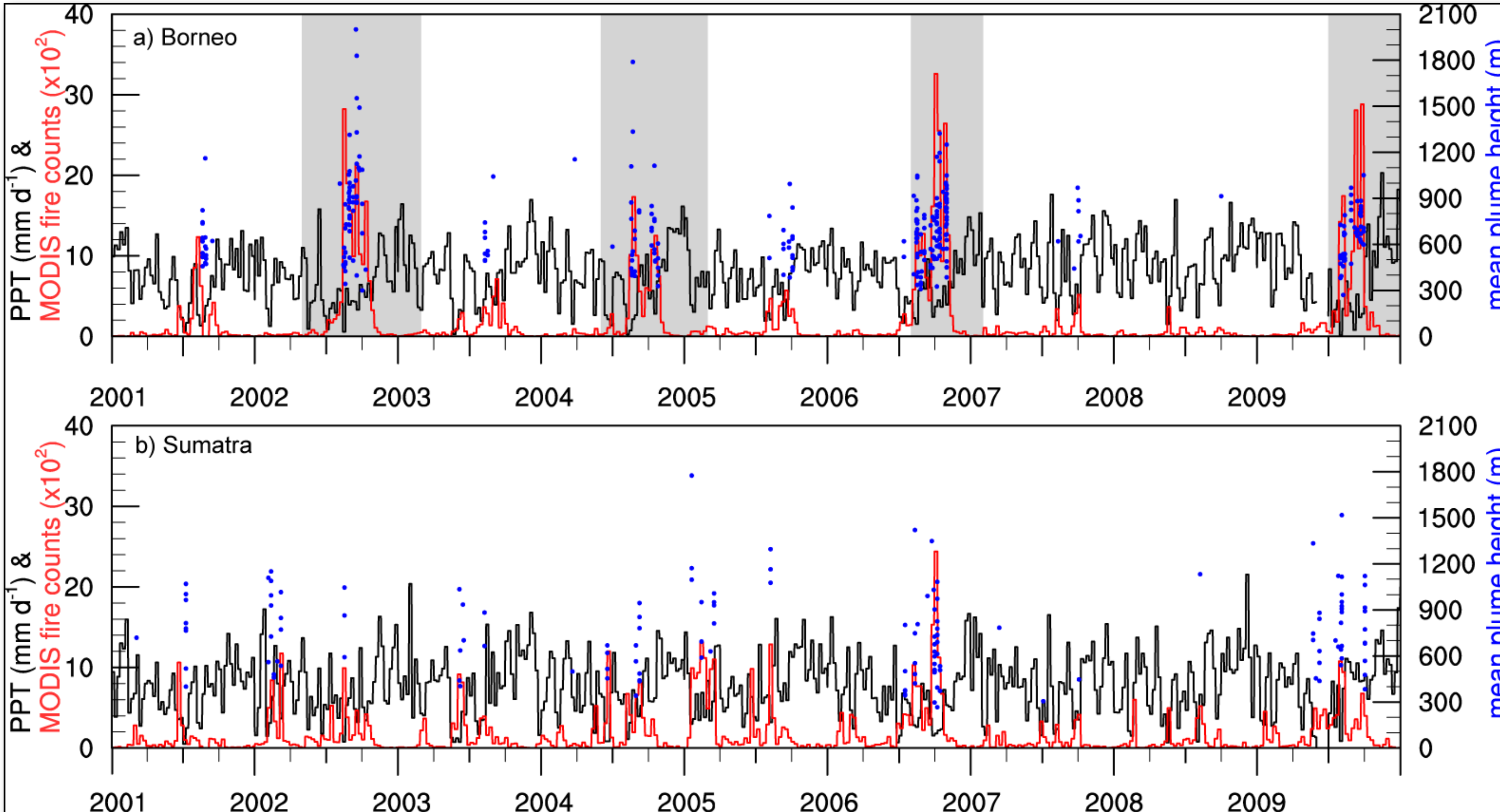


Visibility records from airports record no significant smoke events prior to 1985 despite incidence of drought and El Niño.

from: Field et al., 2009

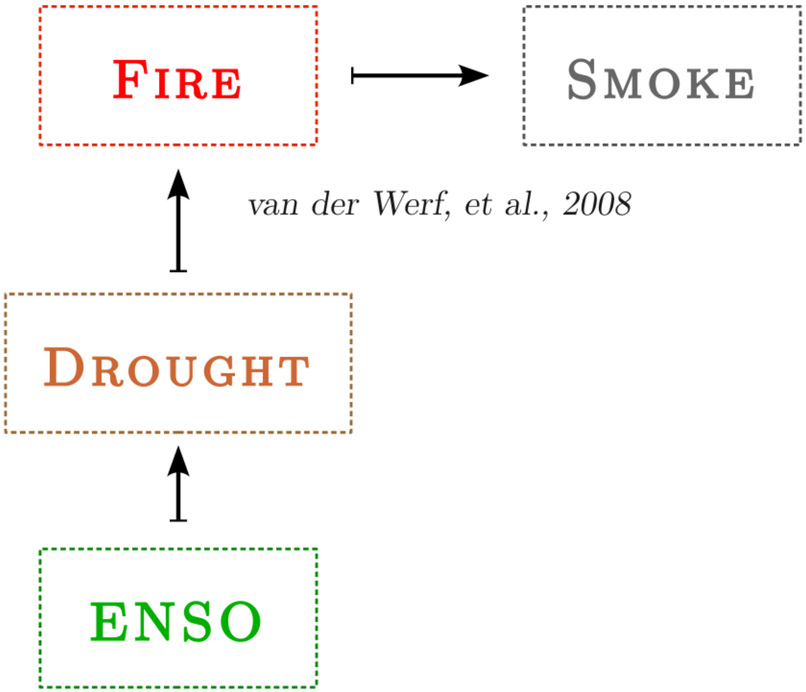
Extreme fire events during El Niño

- ➢ 10-year time series of fire in equatorial Asia from MODIS/MISR
- ➢ Gray bars indicate El Niño events; 80% of fires during 2001-2009 during El Niño



from: Tosca et al., 2011

Proposed feedback loop



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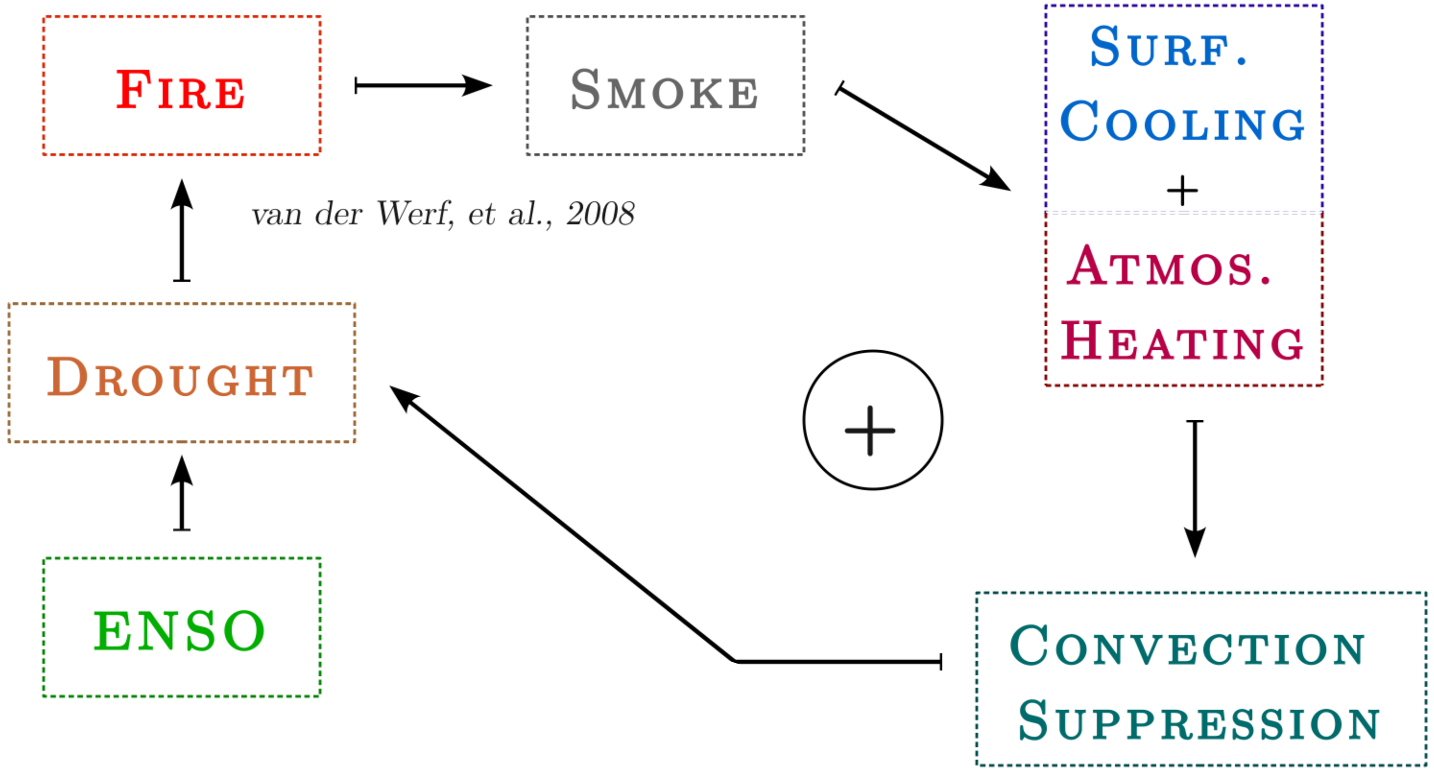

Characterizing the vertical extent of smoke

INITIAL QUESTION: At what vertical level is smoke primarily injected?

from: Tosca et al., 2011

Characterizing the vertical extent of smoke

INITIAL QUESTION: At what vertical level is smoke primarily injected?

WHY WE CARE: Spatially expansive regions of smoke have potentially large climate effects; how do we represent smoke plumes in a climate model?

from: Tosca et al., 2011

Characterizing the vertical extent of smoke

1. Estimating smoke height using the MISR Interactive Explorer (MINX)

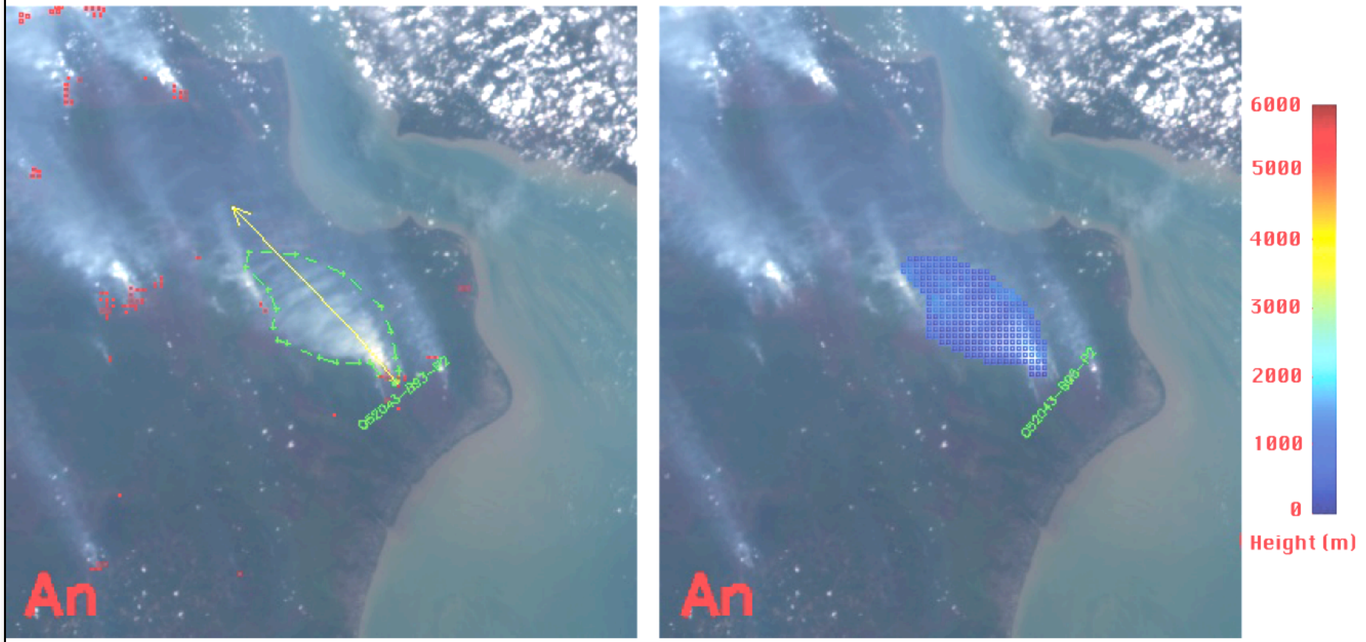

Figure 1. (left) Nadir view of plume showing digitized outline (dashed green line) and interpreted wind direction (yellow arrow). (right) Color-coded, wind-corrected heights superposed on nadir camera view.

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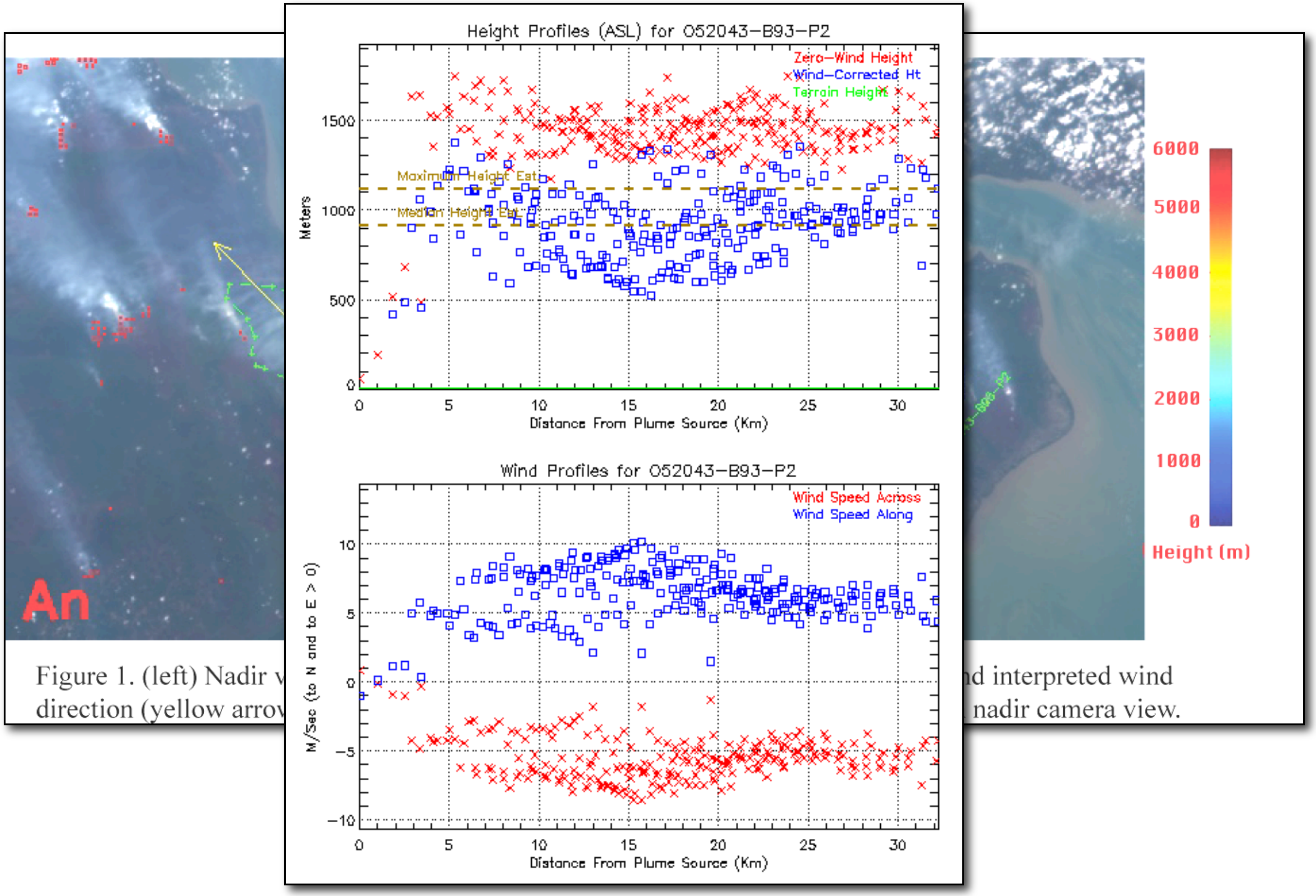
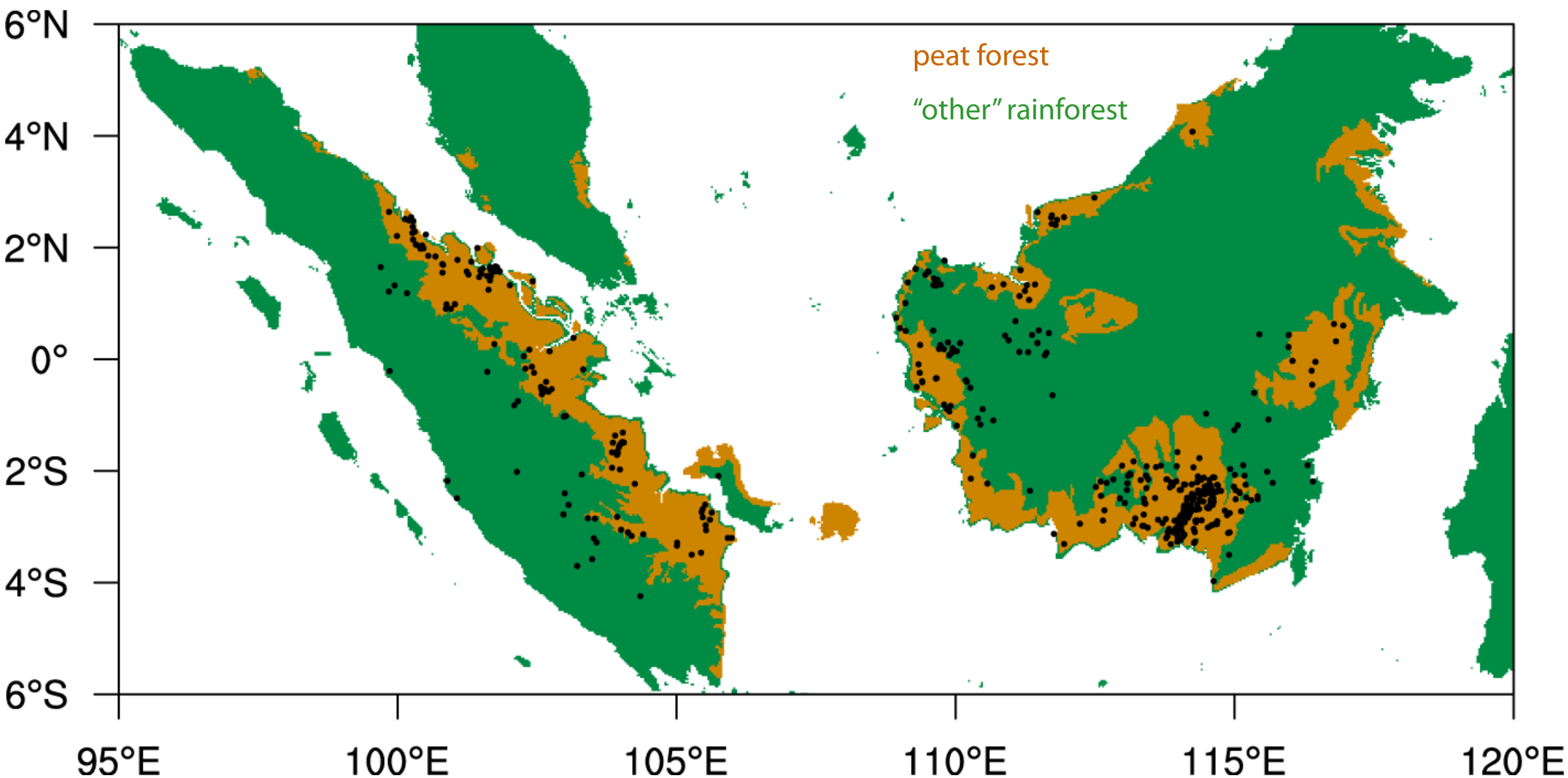


Figure 1. (left) Nadir v… direction (yellow arrov… …d interpreted wind …nadir camera view.

Plume locations

2. Digitized 317 plumes on Borneo and Sumatra from 2001-2009



from:Tosca et al., 2011

Plume locations - insight on injection height?

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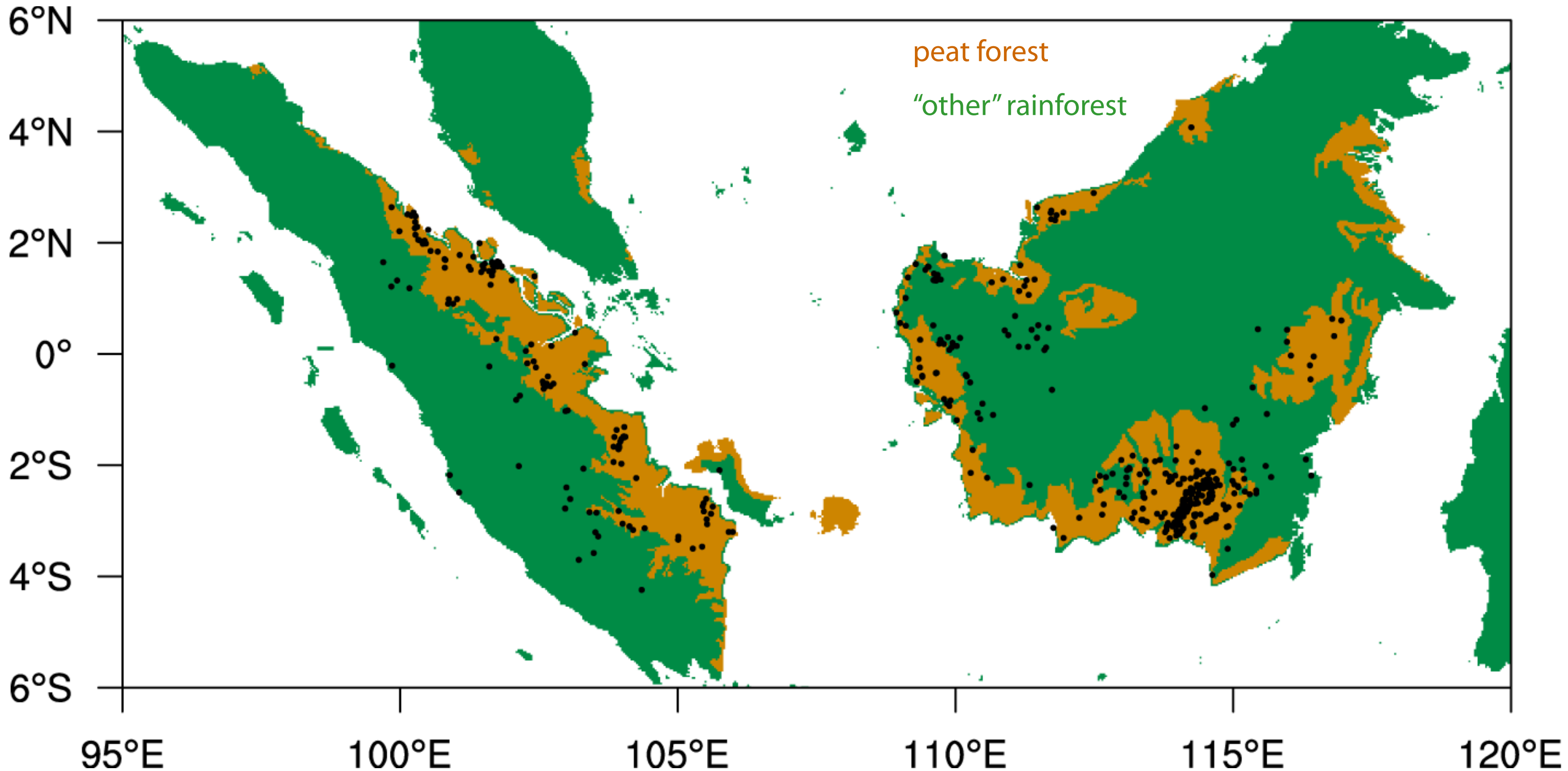


- 75% of plumes in "peat forests" - high soil carbon, high moisture content
  - How will this affect injection height?

from:Tosca et al., 2011

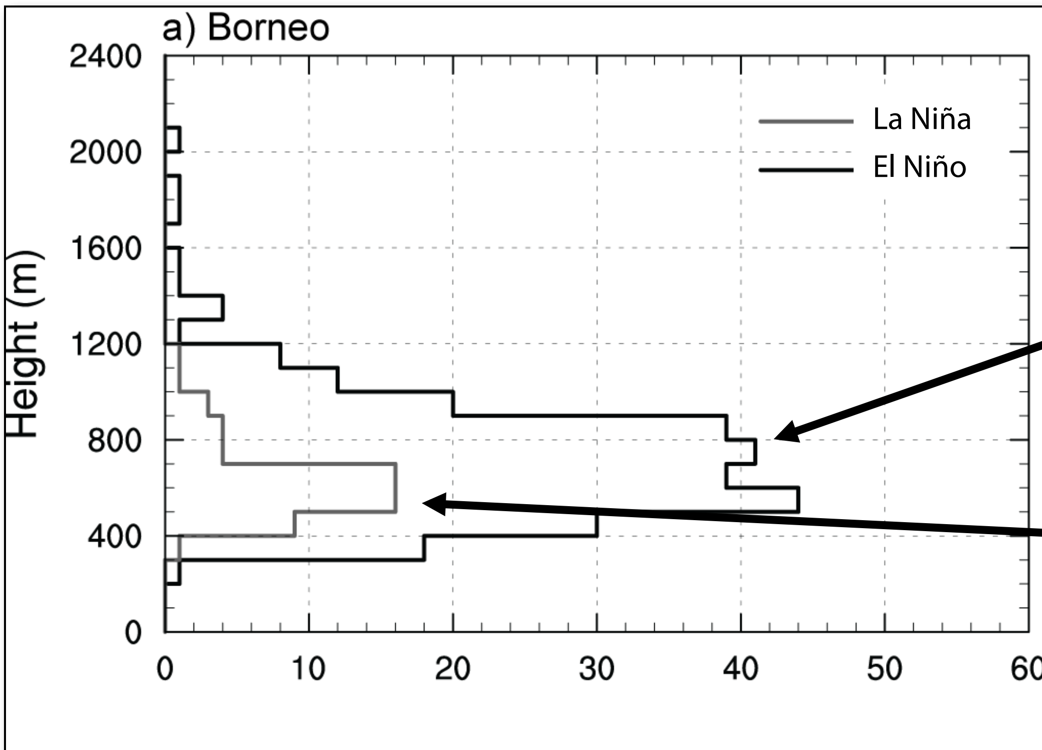
Characterizing the vertical extent of smoke

- 96% of all plumes injected into the Atmospheric Boundary Layer

from:Tosca et al., 2011

Characterizing the vertical extent of smoke

- 96% of all plumes injected into the Atmospheric Boundary Layer (ABL)
- Plumes on Borneo higher during El Niño (dry years), possibly owing to high ABLs



Mean height (El Niño) = 724 ± 16 m

Mean height (La Niña) = 633 ± 23 m

from:Tosca et al., 2011

Characterizing the vertical extent of smoke

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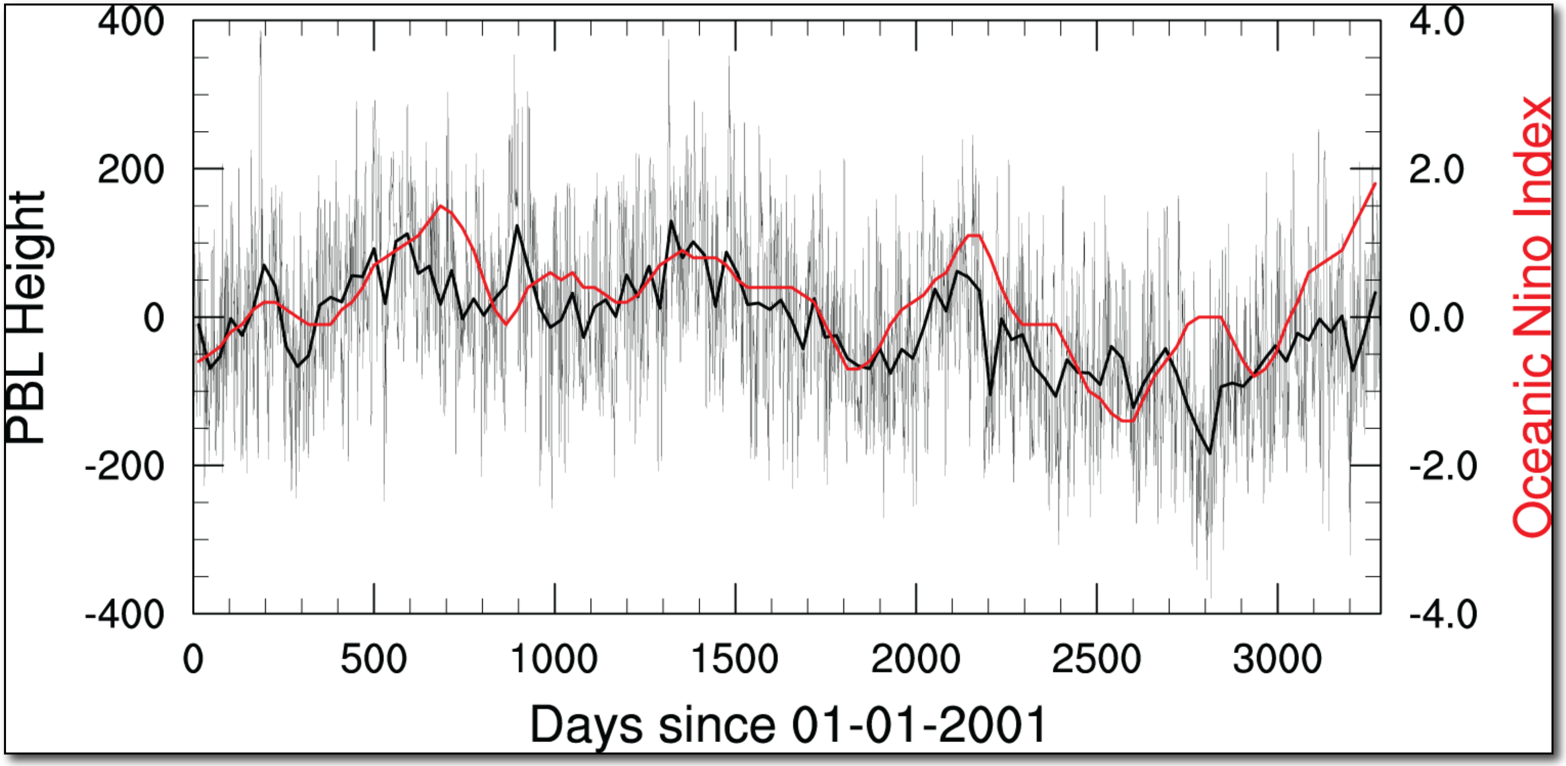
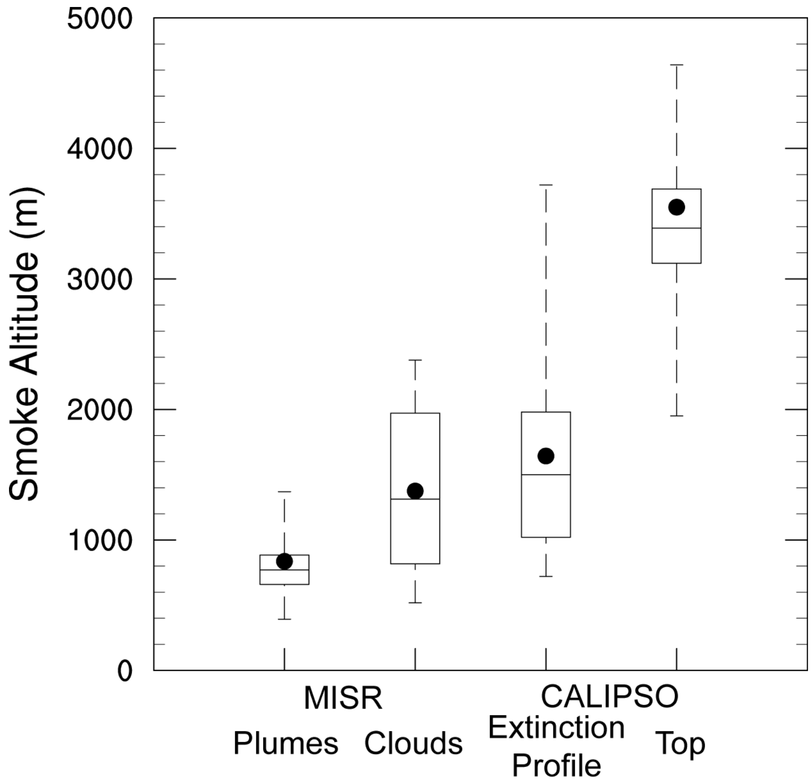


from:Tosca et al., 2011

Smoke plume evolution to smoke clouds

➤ Over time, plumes evolve into "smoke clouds" — regionally expansive, persistent



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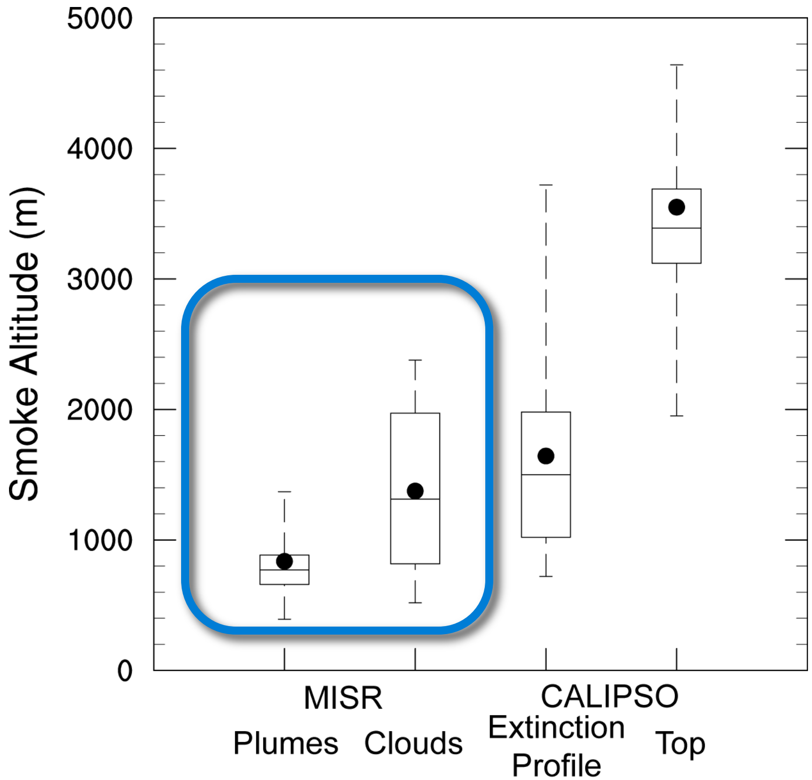
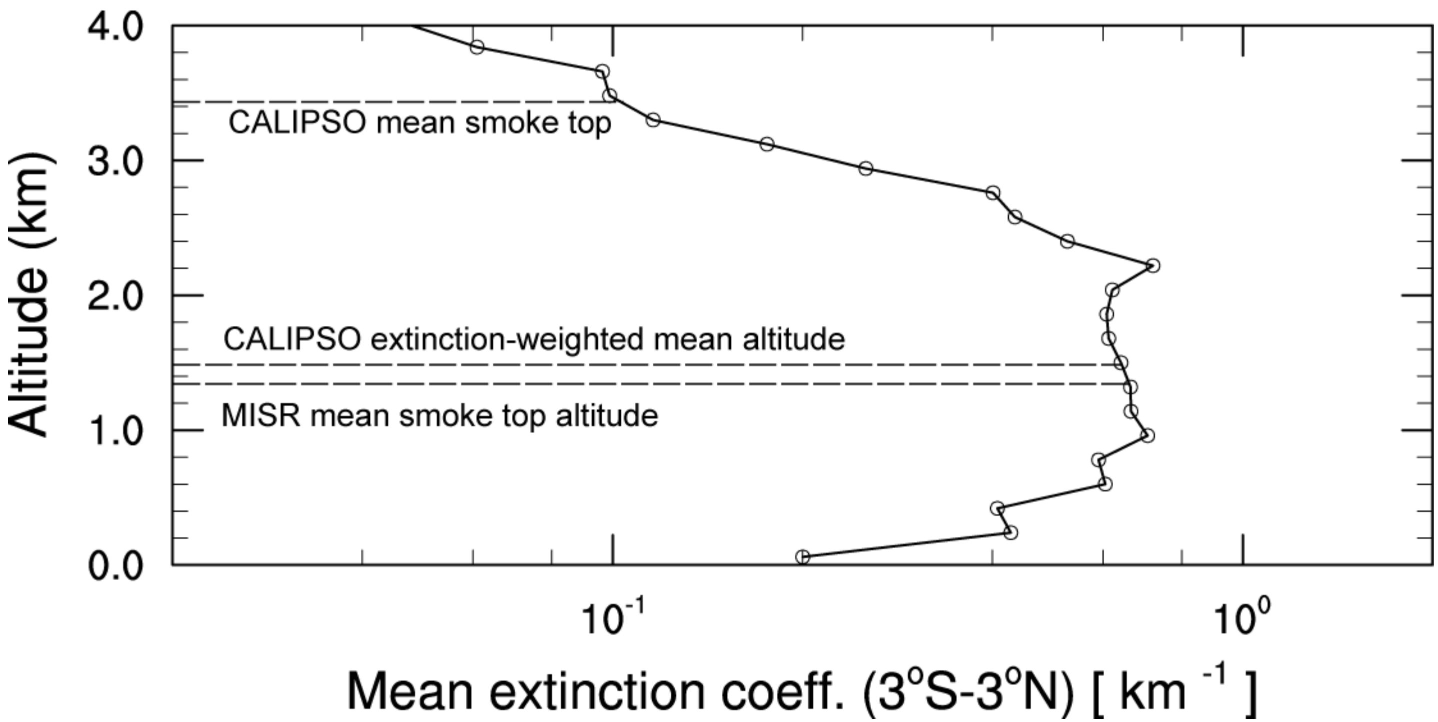


➢ "Smoke clouds" are higher, cover more area, more climatologically important.

from:Tosca et al., 2011

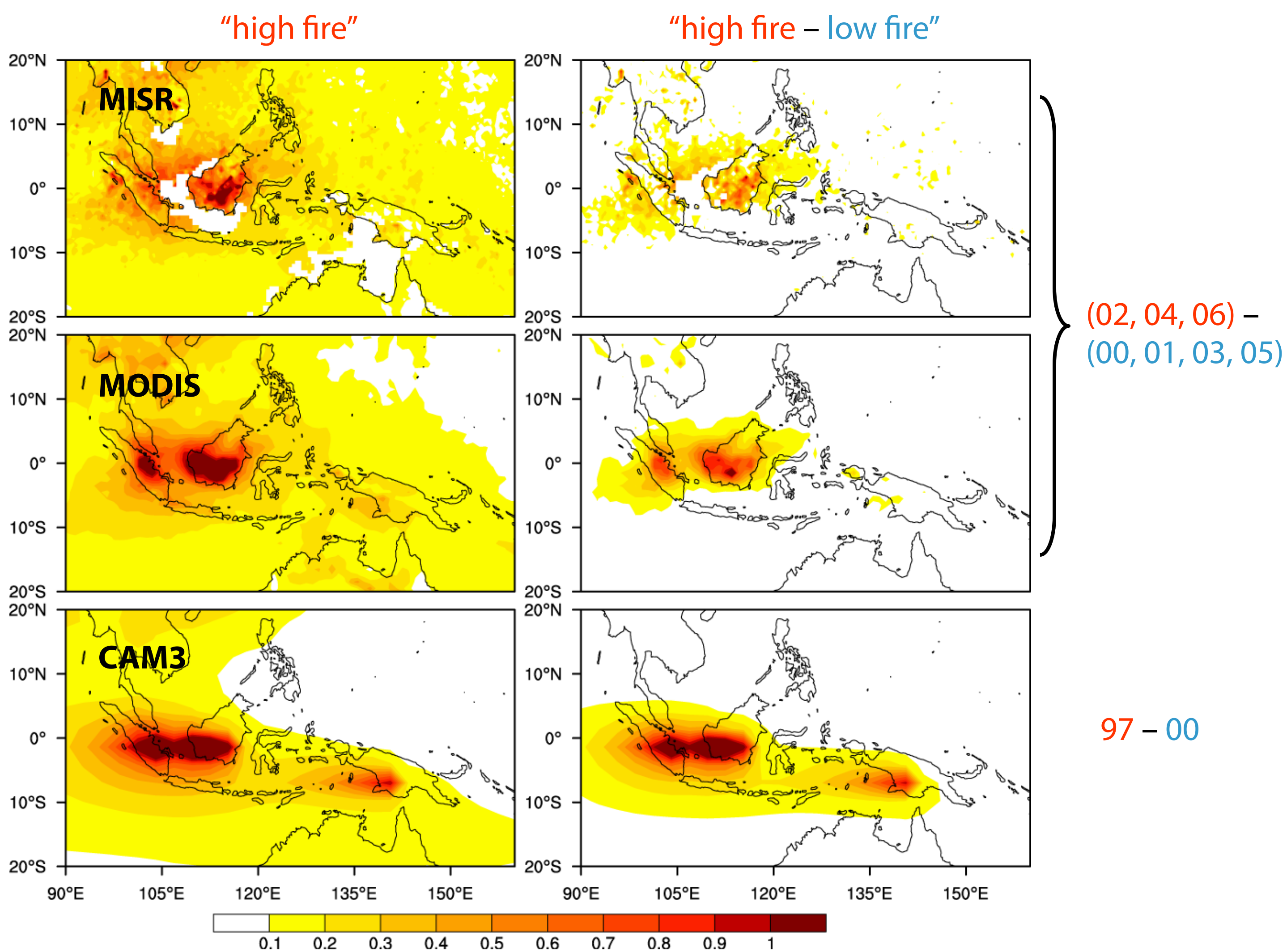
Smoke plume evolution to smoke clouds

- Over time, plumes evolve into "smoke clouds" — regionally expansive, persistent
- Results from CALIPSO confirm MISR observations.



from:Tosca et al., 2011

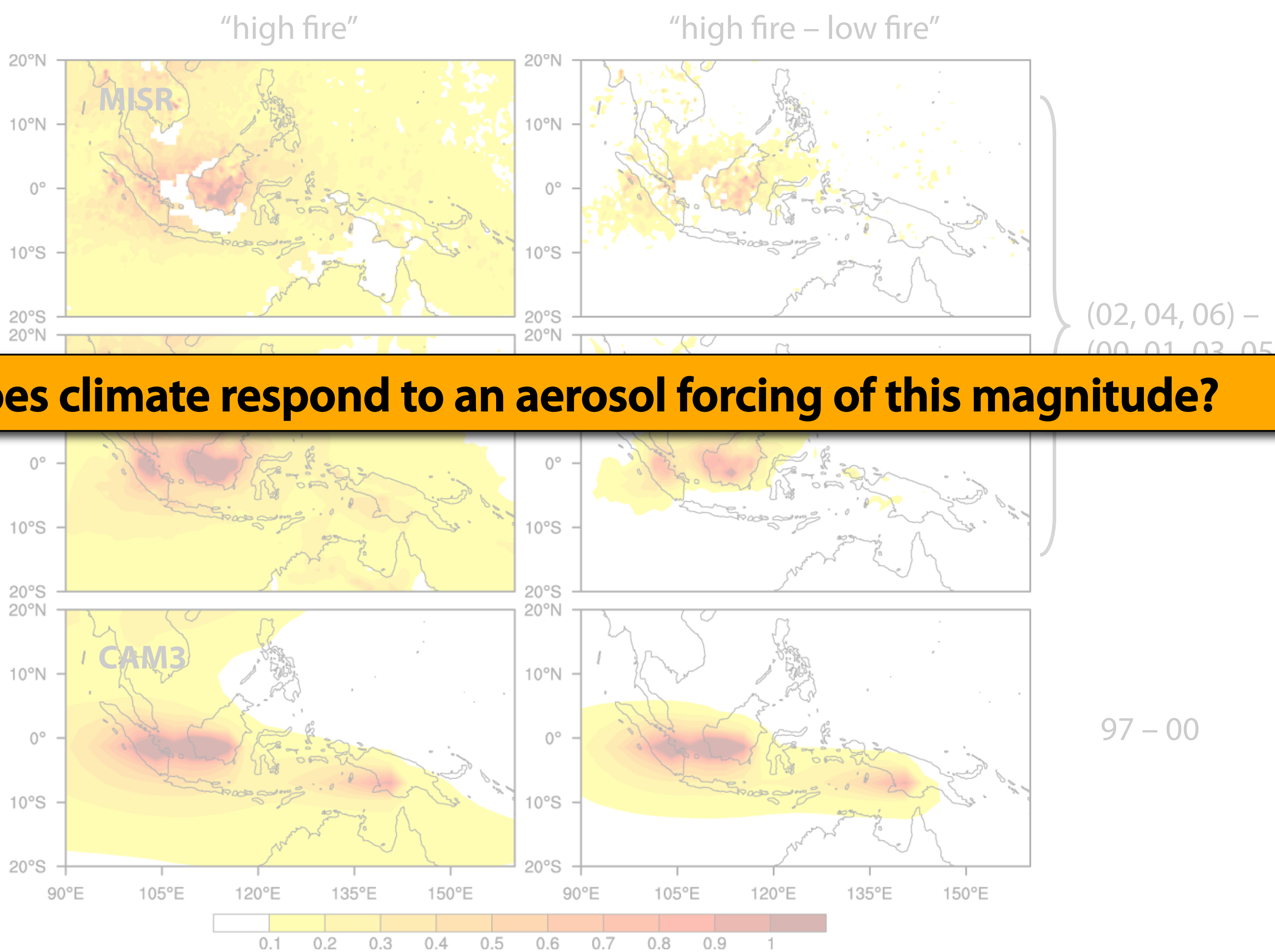
August-October average aerosol optical depth



from: Tosca et al., 2010

➢ Climate response to smoke aerosols in equatorial Asia

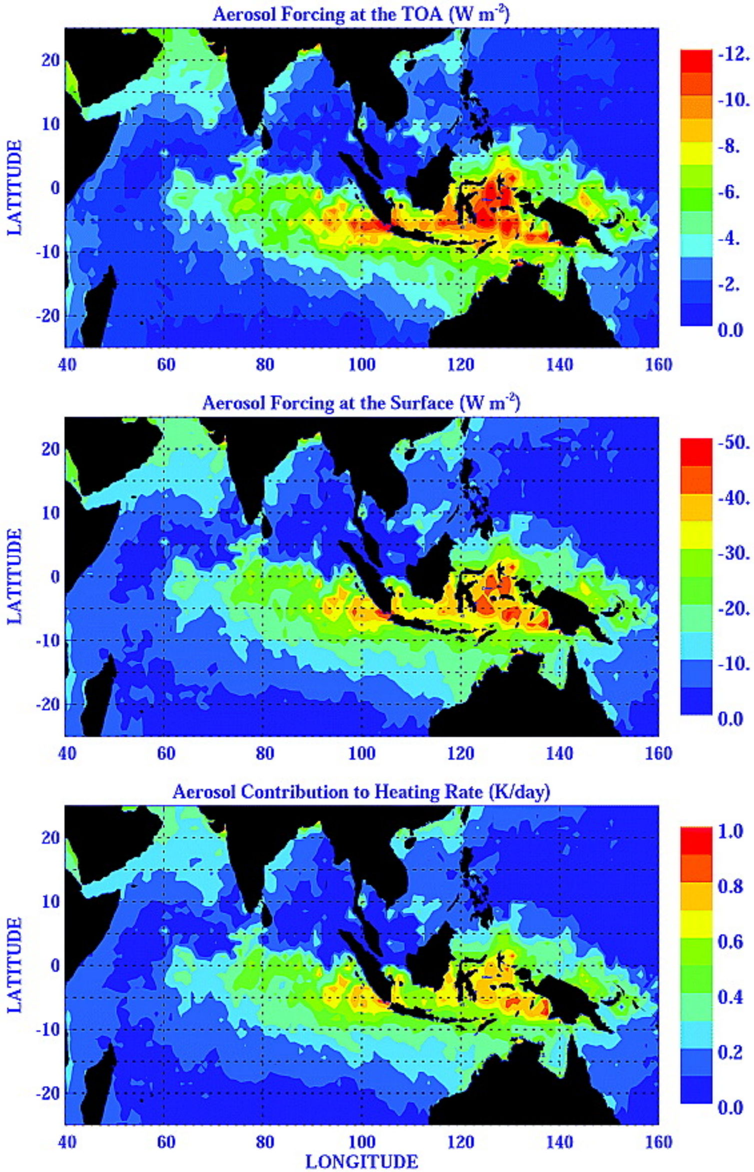
August-October average aerosol optical depth



How does climate respond to an aerosol forcing of this magnitude?

from: Tosca et al., 2010

Radiative forcing from 1997 fires



Podgorny et al., 2003

Method for simulating climate response

1. Force the Community Atmosphere Model (CAM3) w/ monthly-varying, annually repeating **1997** fire emissions from GFED, version 2[1]

2. Force a second simulation with repeating **2000** fire emissions from GFEDv2.

3. Smoke injected into the boundary layer – consistent with injection height work.

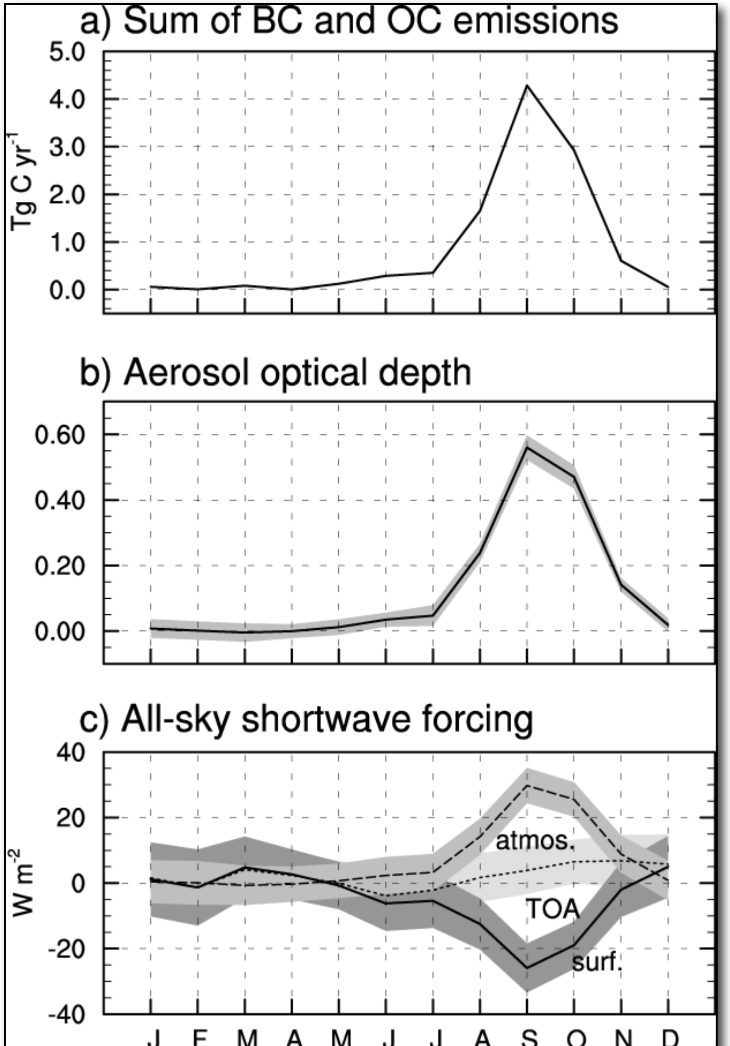
4. Aerosols interacted with radiation directly but not cloud microphysics, therefore our simulations consider the direct and semi-direct effects

5. Each simulation was: 10 year spin-up (not included in averages) + 30 year annually-repeating.

6. "Anomalies" are the difference between HIGHFIRE and LOWFIRE.

[1]van der Werf et al., 2006

Seasonal mean climate forcing (HIGHFIRE – LOWFIRE)



- Smoke (BC & OC) emissions peak from August through November over Indonesia
- Aerosol optical depth also peaks during this time, with maximum area-averaged anomalies of 0.5-0.6 during September

from: Tosca et al., 2010

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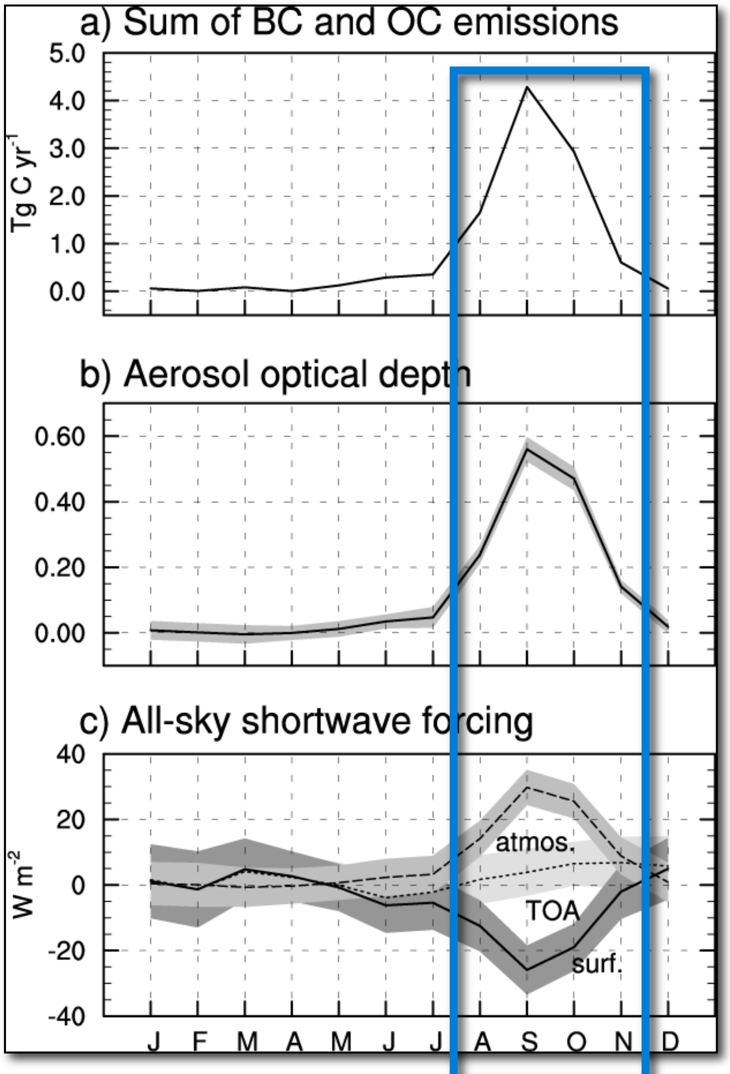

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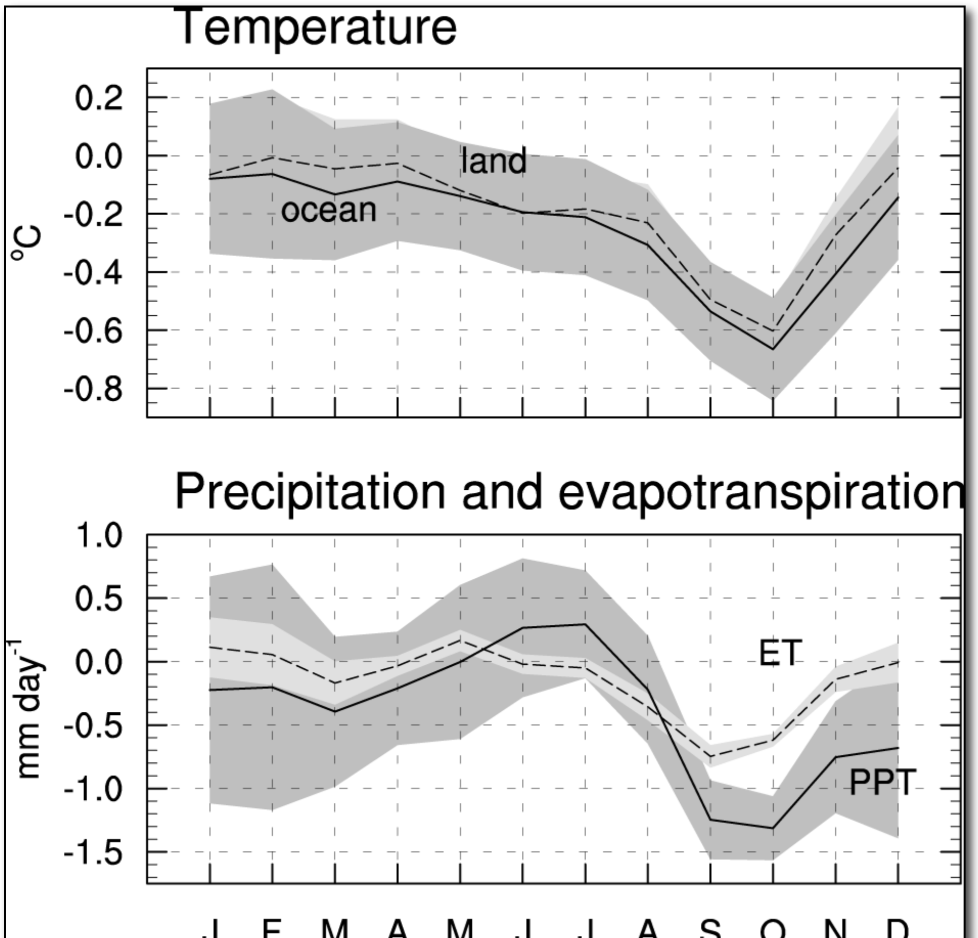
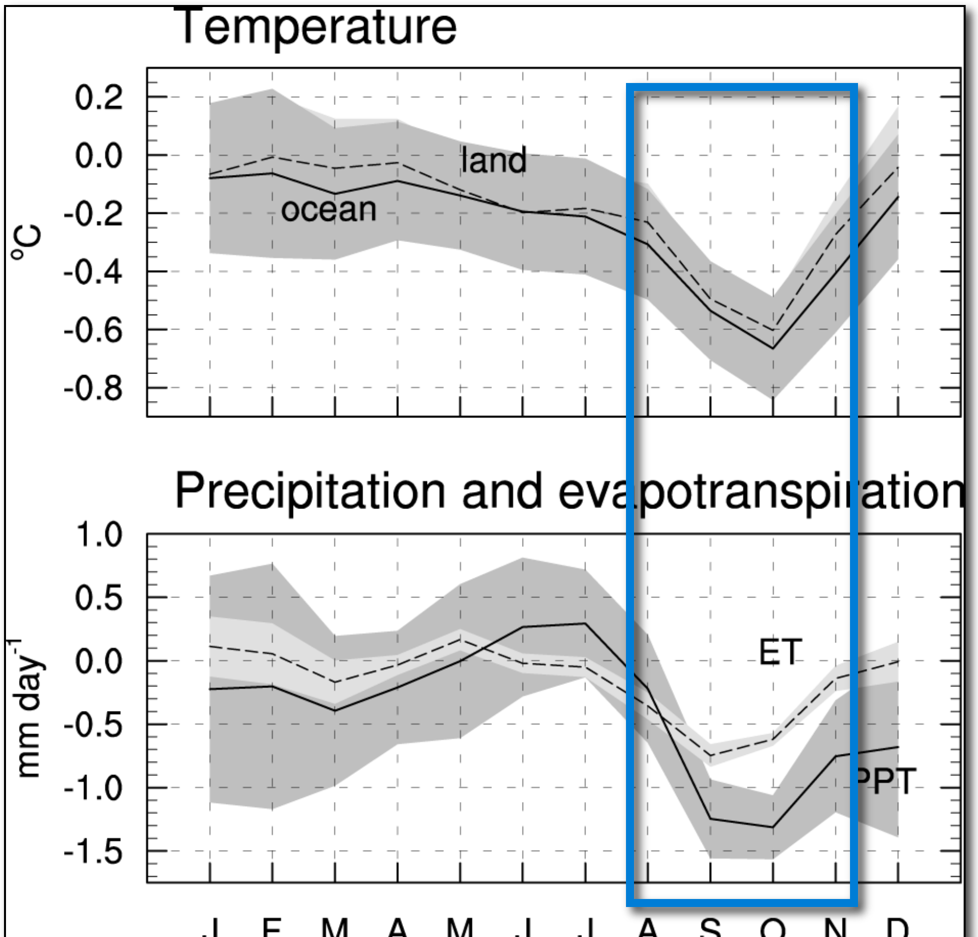
Seasonal mean climate response



- Smoke (BC & OC) emissions peak from August through November over Indonesia
- Aerosol optical depth also peaks during this time, with maximum area-averaged anomalies of 0.5-0.6 during September
- Surface cooling, atmospheric warming, near-zero (slightly positive) TOA RF.
- Ocean and land temperatures cooled significantly (–0.6°C in October) — one month lag in response to forcing
- Precipitation signficantly reduced (10%) during September and October
- Evaporation also decreases = drought conditions develop.

from: Tosca et al., 2010

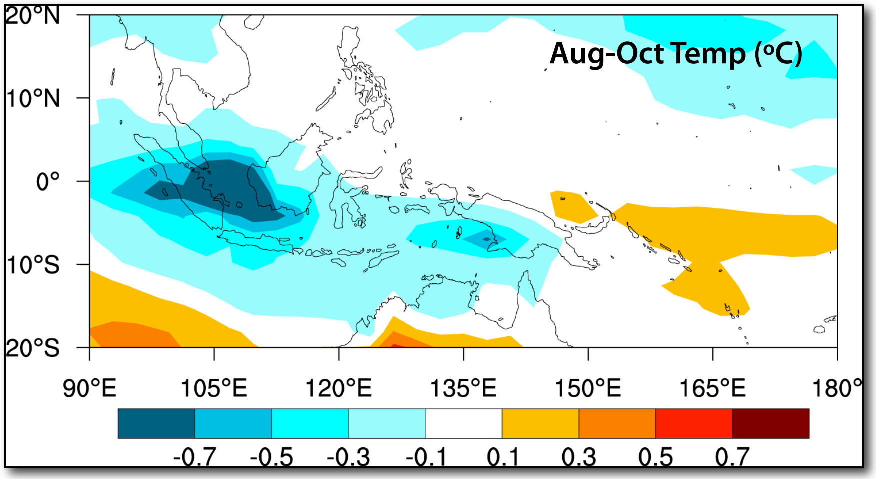
Seasonal mean climate response



- Smoke (BC & OC) emissions peak from August through November over Indonesia
- Aerosol optical depth also peaks during this time, with maximum area-averaged anomalies of 0.5-0.6 during September
- Surface cooling, atmospheric warming, near-zero (slightly positive) TOA RF.
- Ocean and land temperatures cooled significantly (–0.6°C in October) — one month lag in response to forcing
- Precipitation signficantly reduced (10%) during September and October
- Evaporation also decreases = drought conditions develop.

from: Tosca et al., 2010

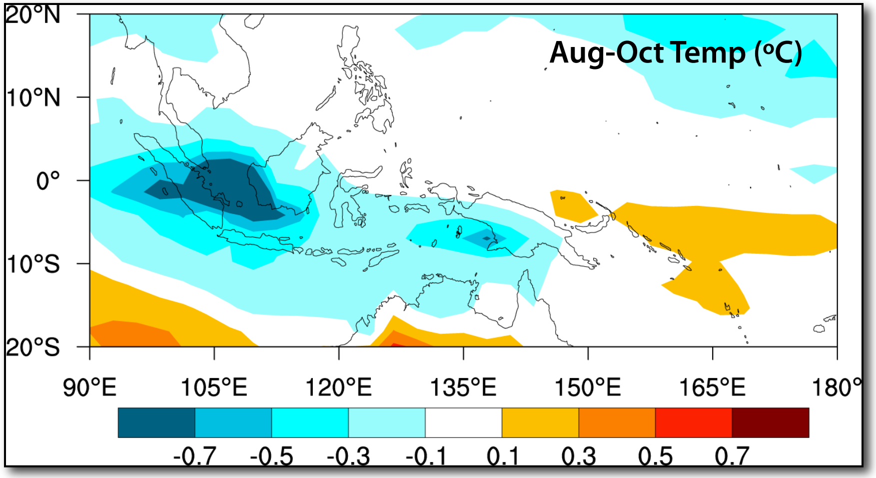
Mechanisms for precipitation response



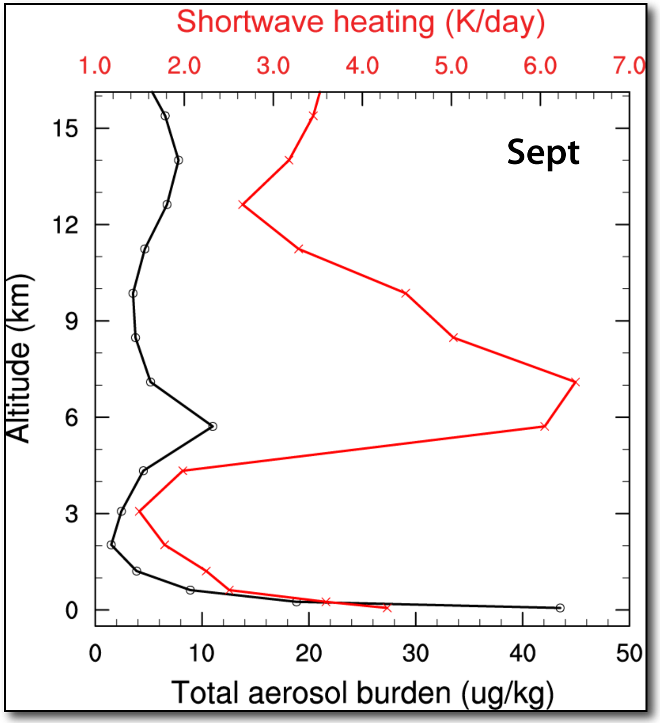
- ➢ Large area of reduced surface temperatures

from: Tosca et al., 2010

Mechanisms for precipitation response



- ➢ Large area of reduced surface temperatures
- ➢ Increased solar heating aloft



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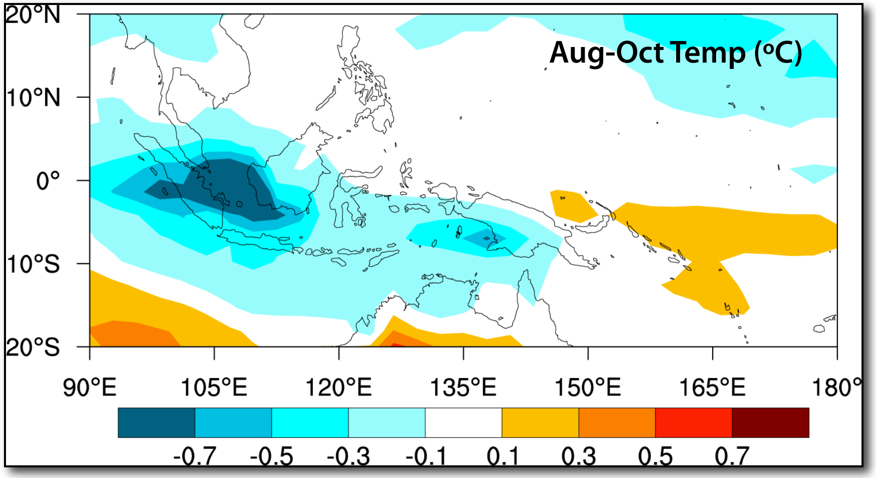
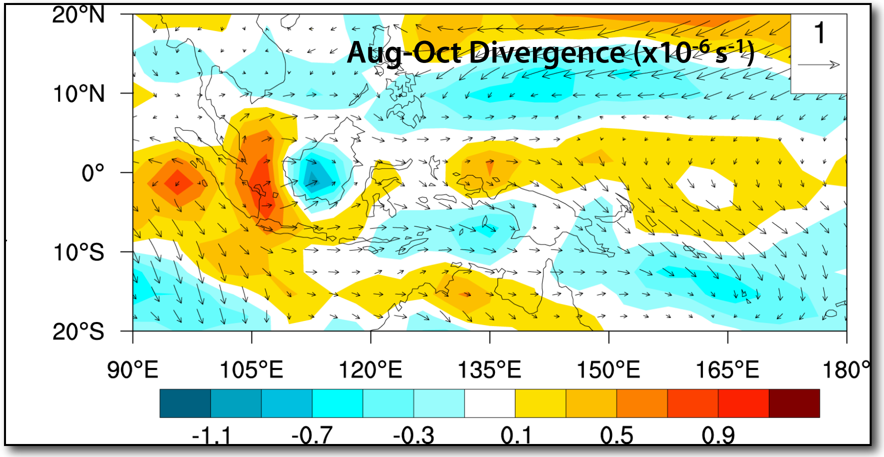
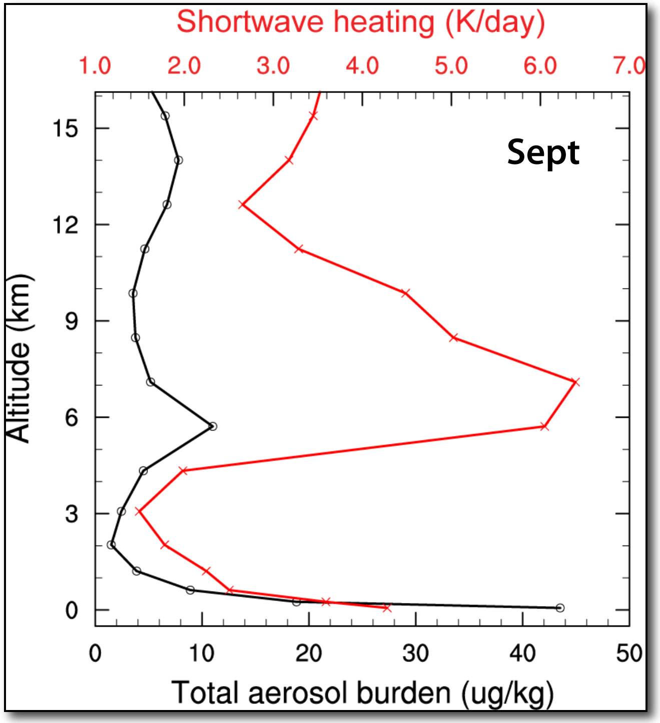


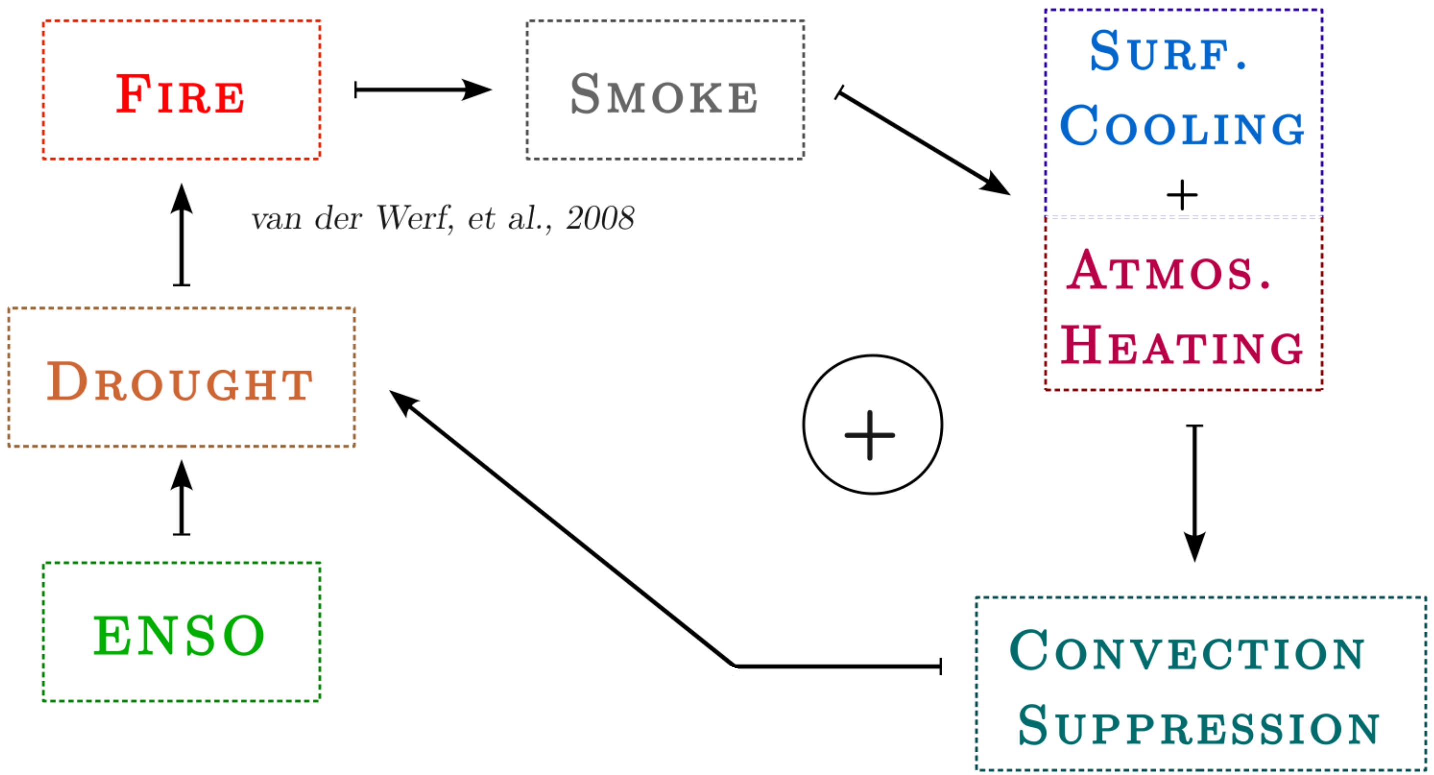
- Large area of reduced surface temperatures
- Increased solar heating aloft
- Increase subsidence at the surface, limit convection = reduce precipitation.





from: Tosca et al., 2010

Evidence for a feedback …



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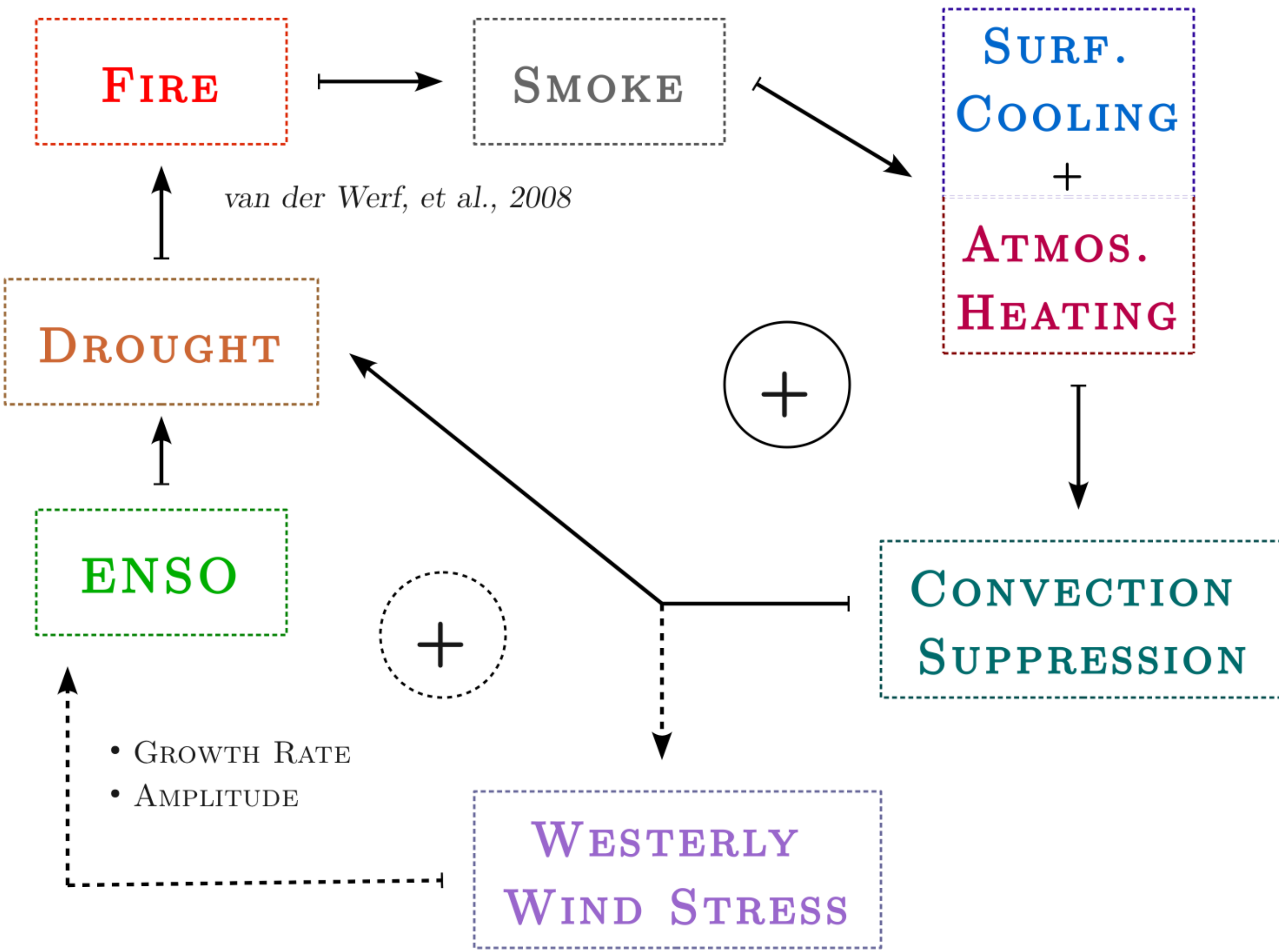

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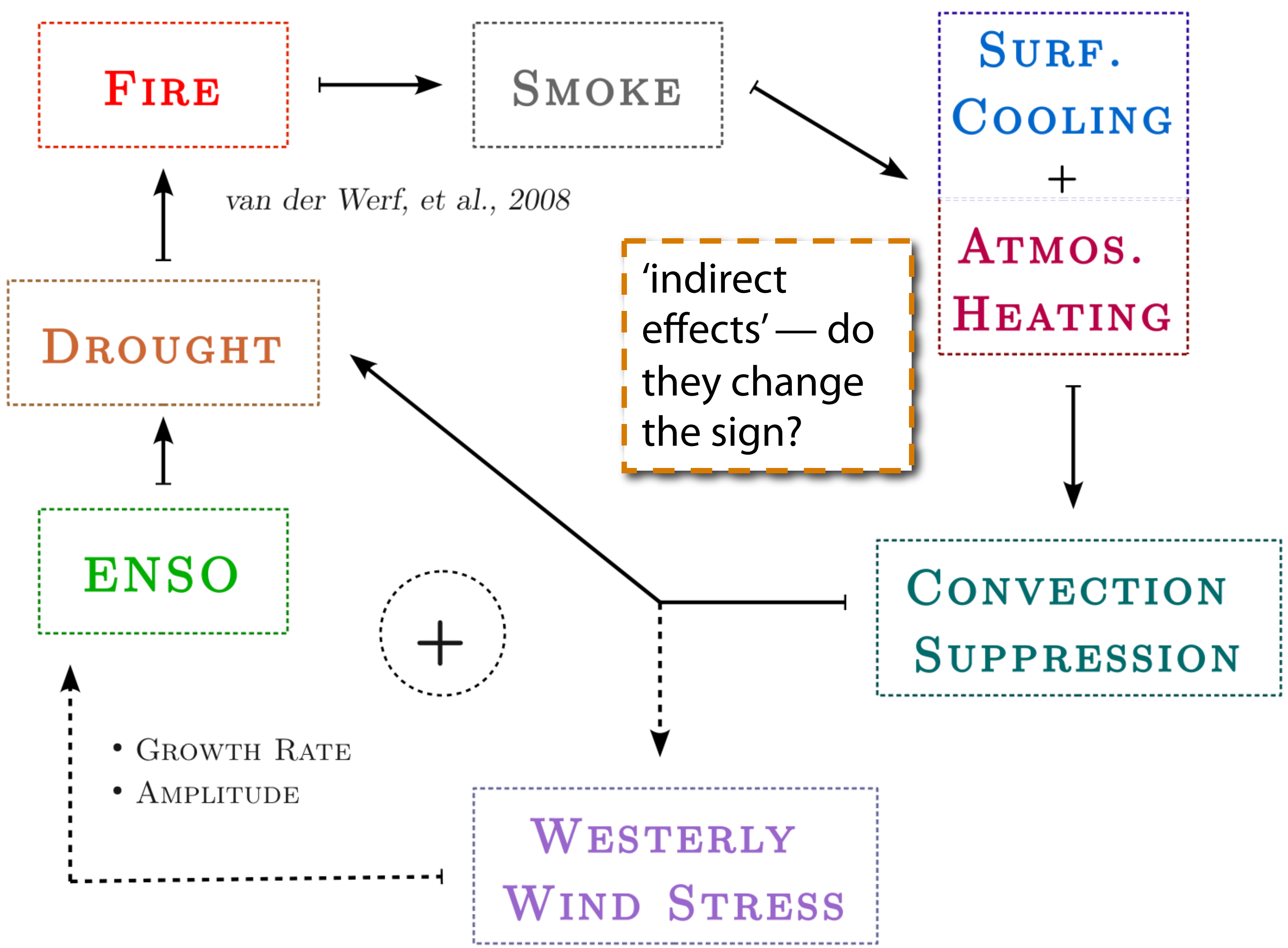


Global response?

BIG QUESTION: WHAT IS THE GLOBAL CLIMATE IMPACT OF FIRE AEROSOLS?

from: Tosca et al., 2012

Global response?

BIG QUESTION: WHAT IS THE GLOBAL CLIMATE IMPACT OF FIRE AEROSOLS?

Caveat: We want to accurately simulate the magnitude of the forcing – requires matching simulated optical depths to observations.

from: Tosca et al., 2012

Method for simulating climate response

1. Force Community Atmosphere Model, version 5 (CAM5) with monthly varying emissions from 1997–2009.

2. Scale emissions in burning regions by optimizing simulated optical depths using MISR/MODIS satellite data

3. Experimental simulations:

   A. 15-year spin-up; 4 cycles of monthly repeating emissions (1997-2009), 52 years total (FIRE)

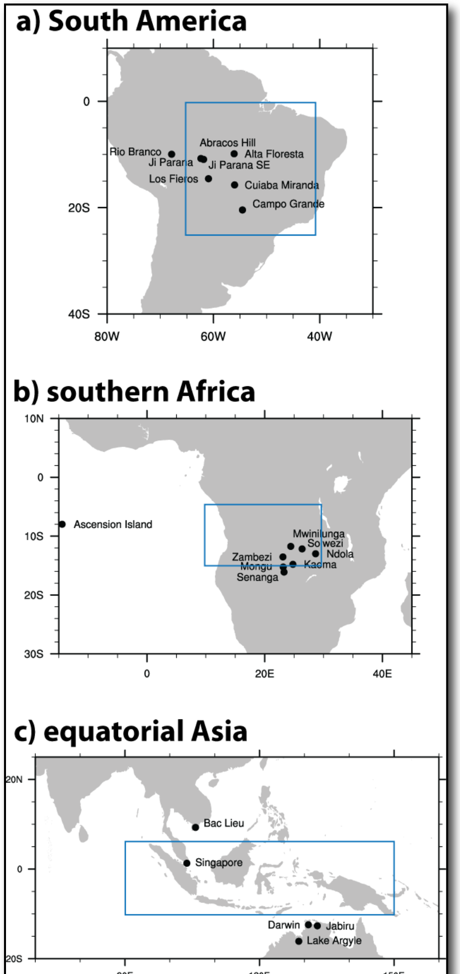
   B. 15-year spin-up; no smoke emissions, all other variables same as (A). (NOFIRE)

4. Climate "response" to fire aerosols is interpreted as FIRE – NOFIRE. Simulations consider direct, semi-direct, & indirect effects

from: Tosca et al., 2012

➢ Climate response to smoke aerosols *globally*

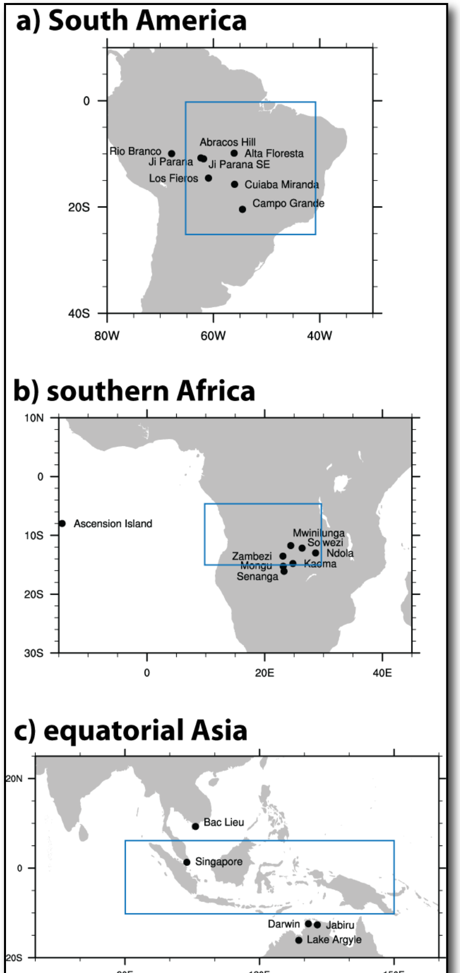
Scaling emissions



➢ Choose regions where fire aerosols are dominant contributor to area-wide optical depth

from: Tosca et al., 2012

Scaling emissions



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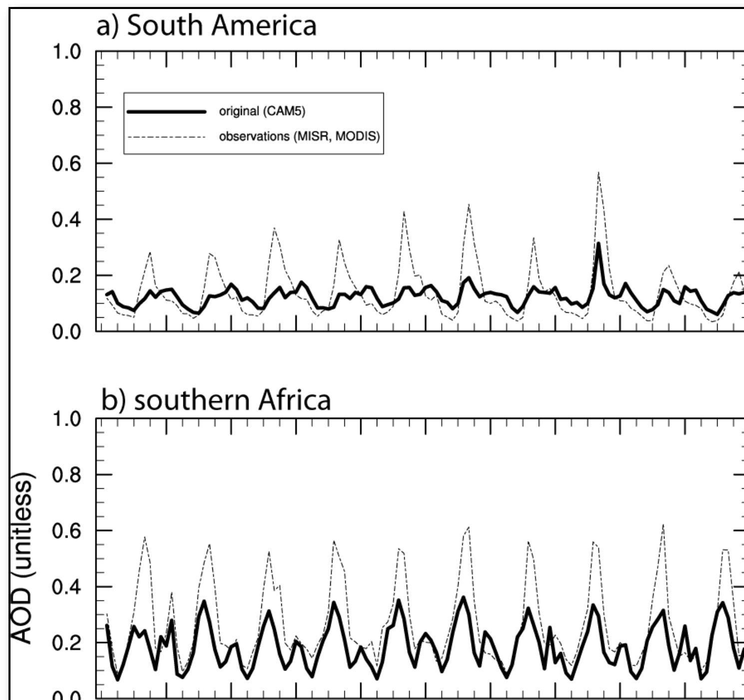
➢ CAM5 massively underestimates optical depth from fires — remedy = scale emissions upward.



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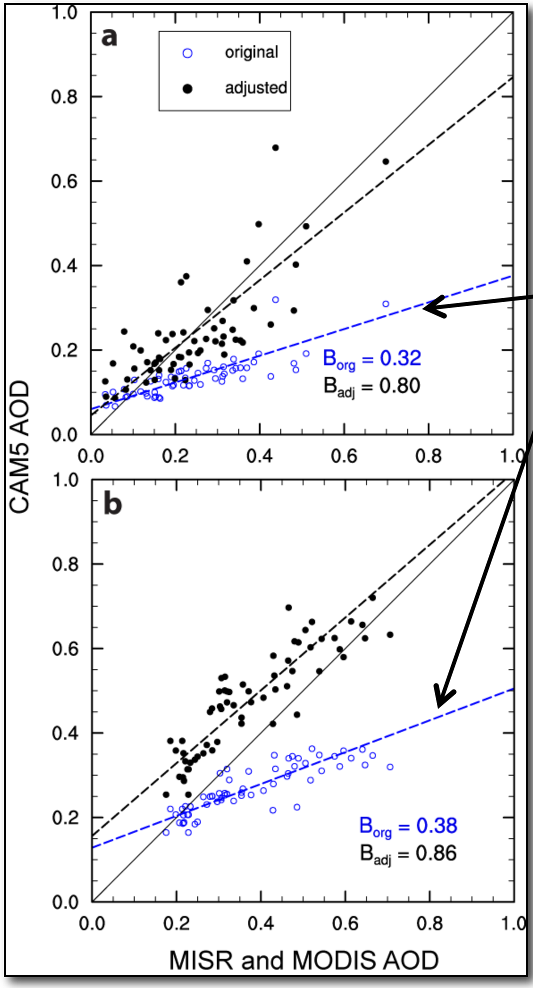

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- ➢ CAM5 massively underestimates optical depth from fires — remedy = scale emissions upward.
- ➢ Regression slopes between simulations with original emissions and observations were 0.3-0.4 — too low.

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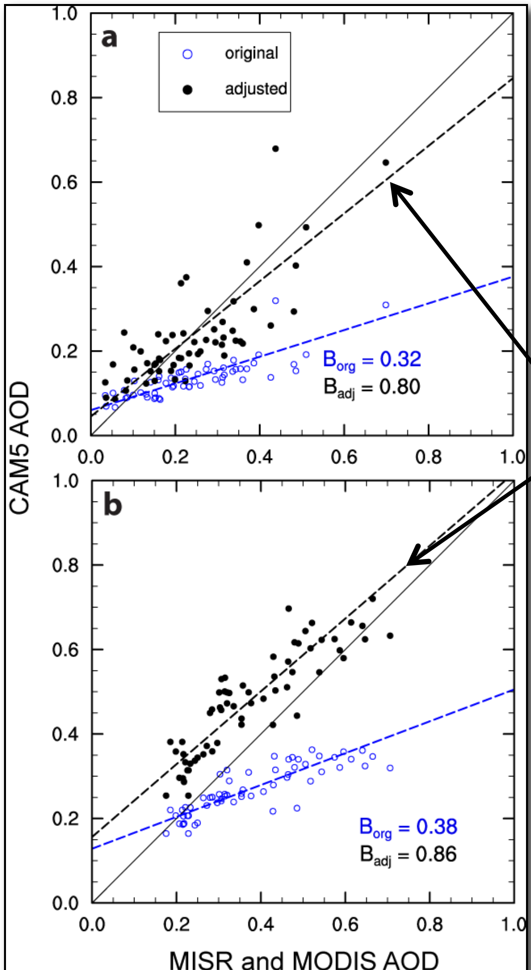

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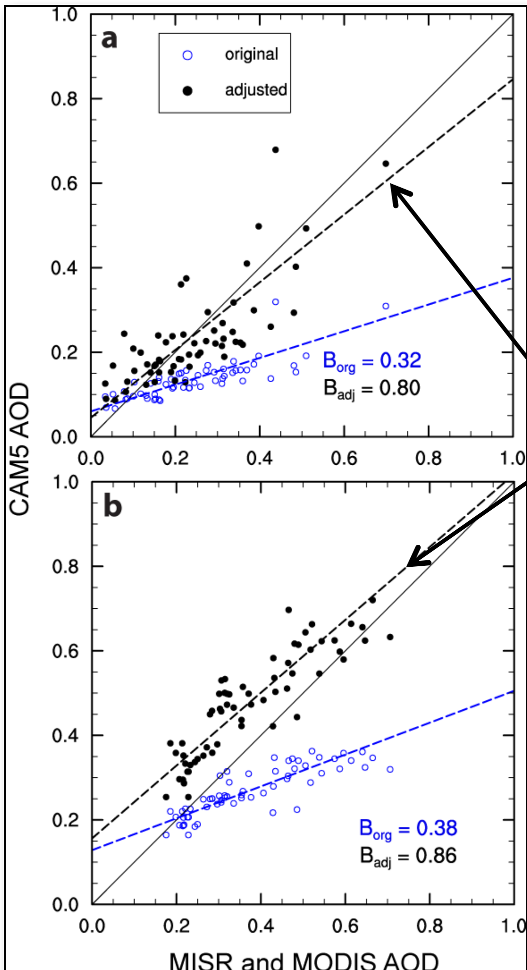
➢ After scaling, simulated optical depths were better correlated with observations

from: Tosca et al., 2012

Scaling emissions



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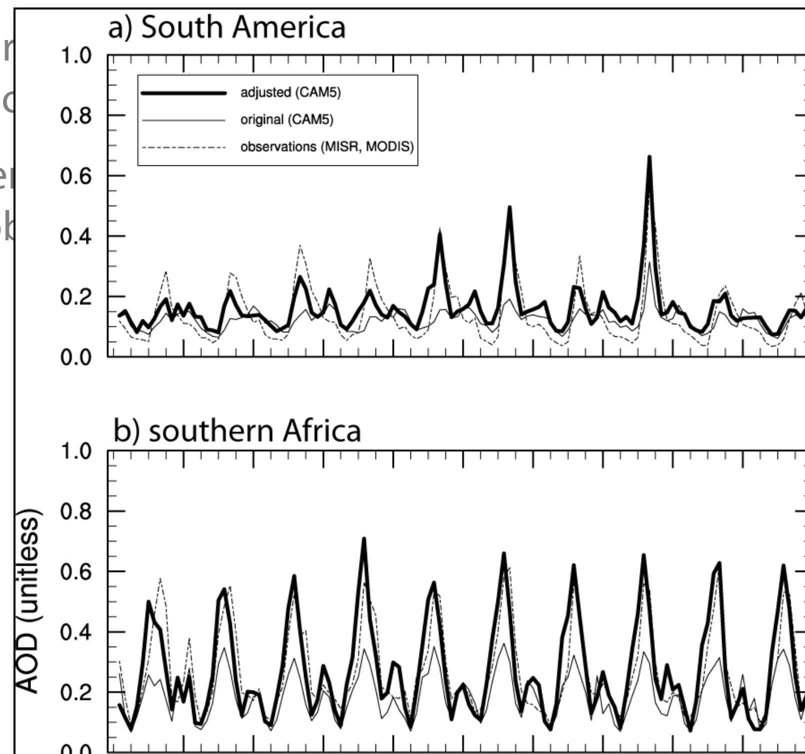


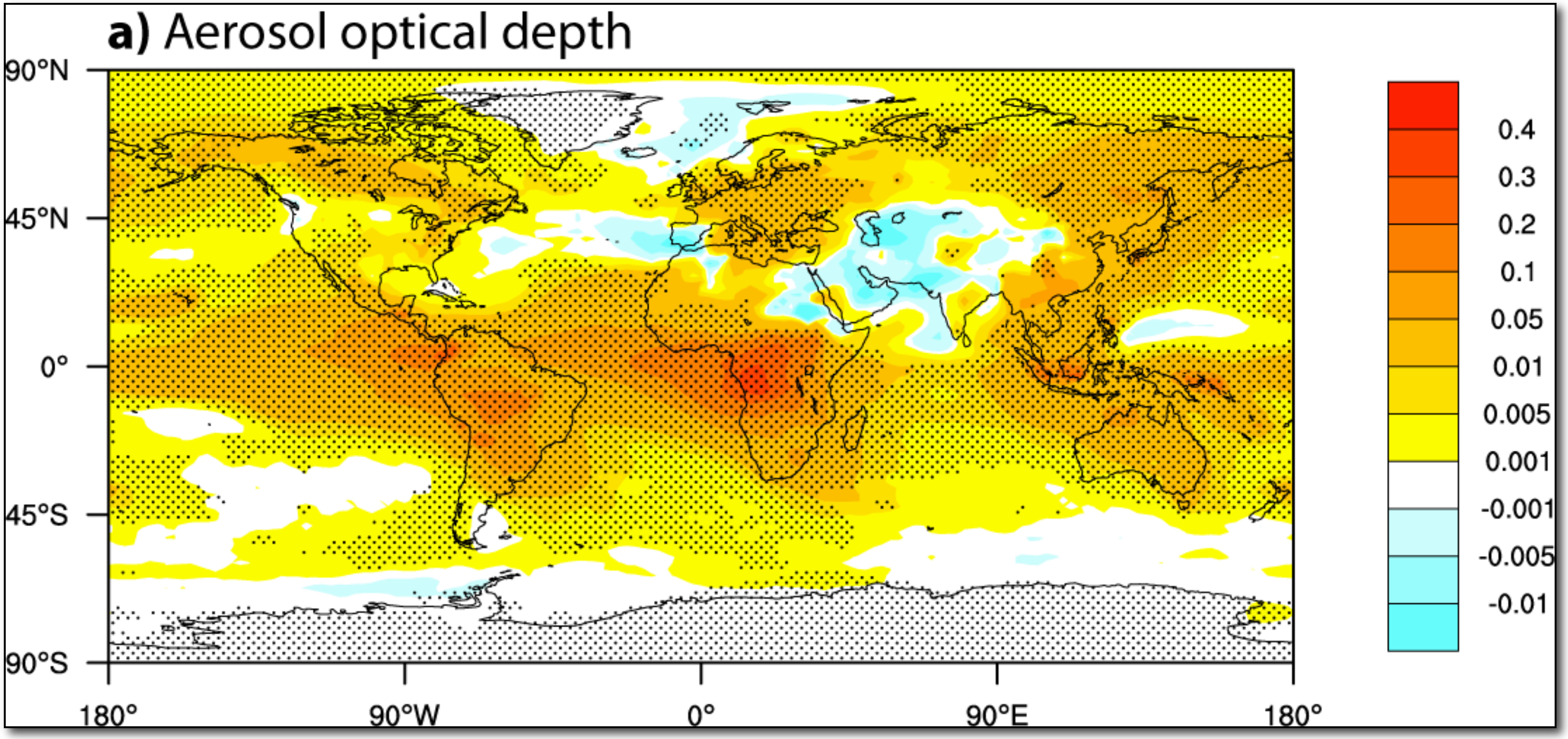
from: Tosca et al., 2012

Annual climate response

from: Tosca et al., 2012

Optical depth "forcing"

➢ Globally, aerosol optical depth increased 13% (+0.02) due to fire aerosols

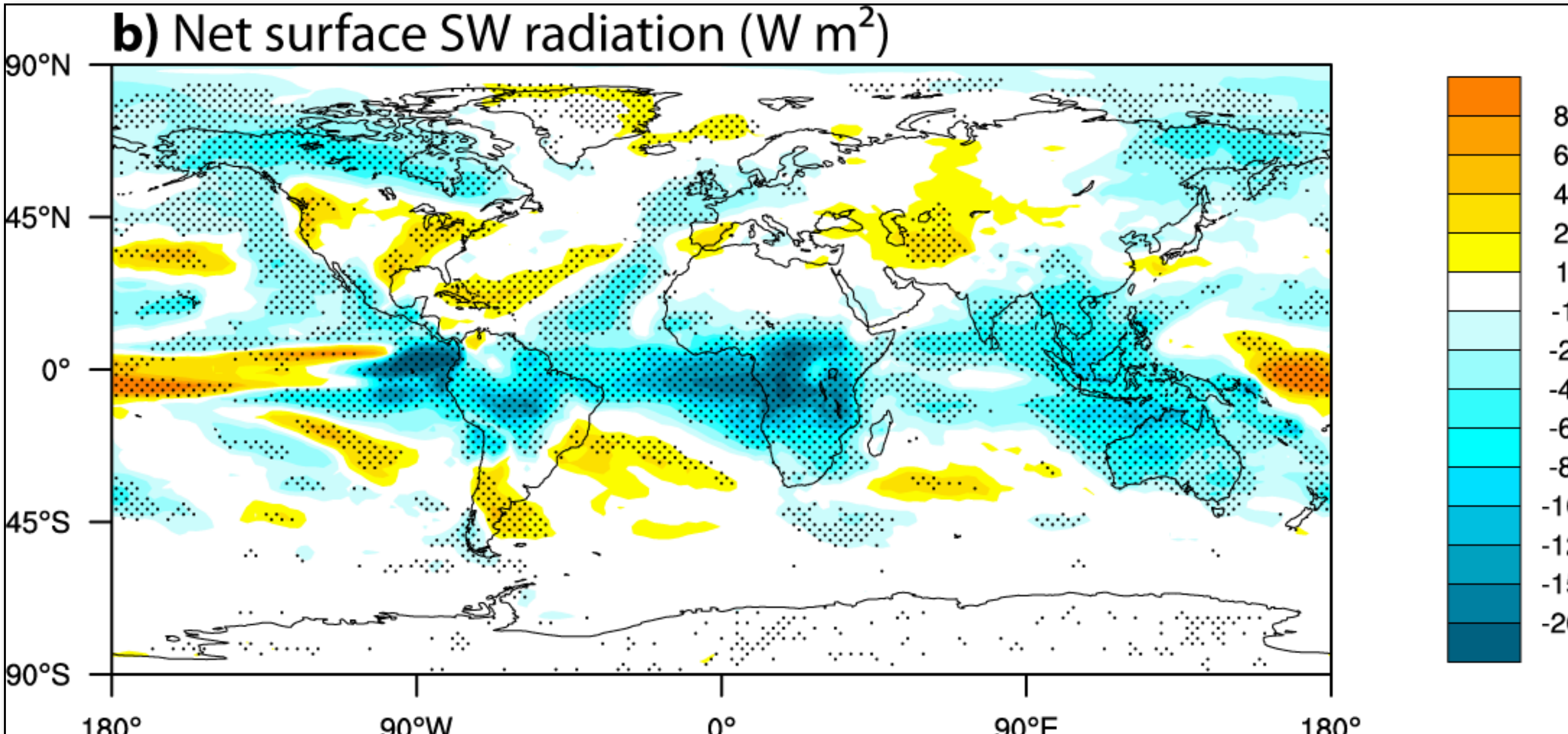


stippling is 95% confidence interval (student t-test)

from: Tosca et al., 2012

Surface radiation response

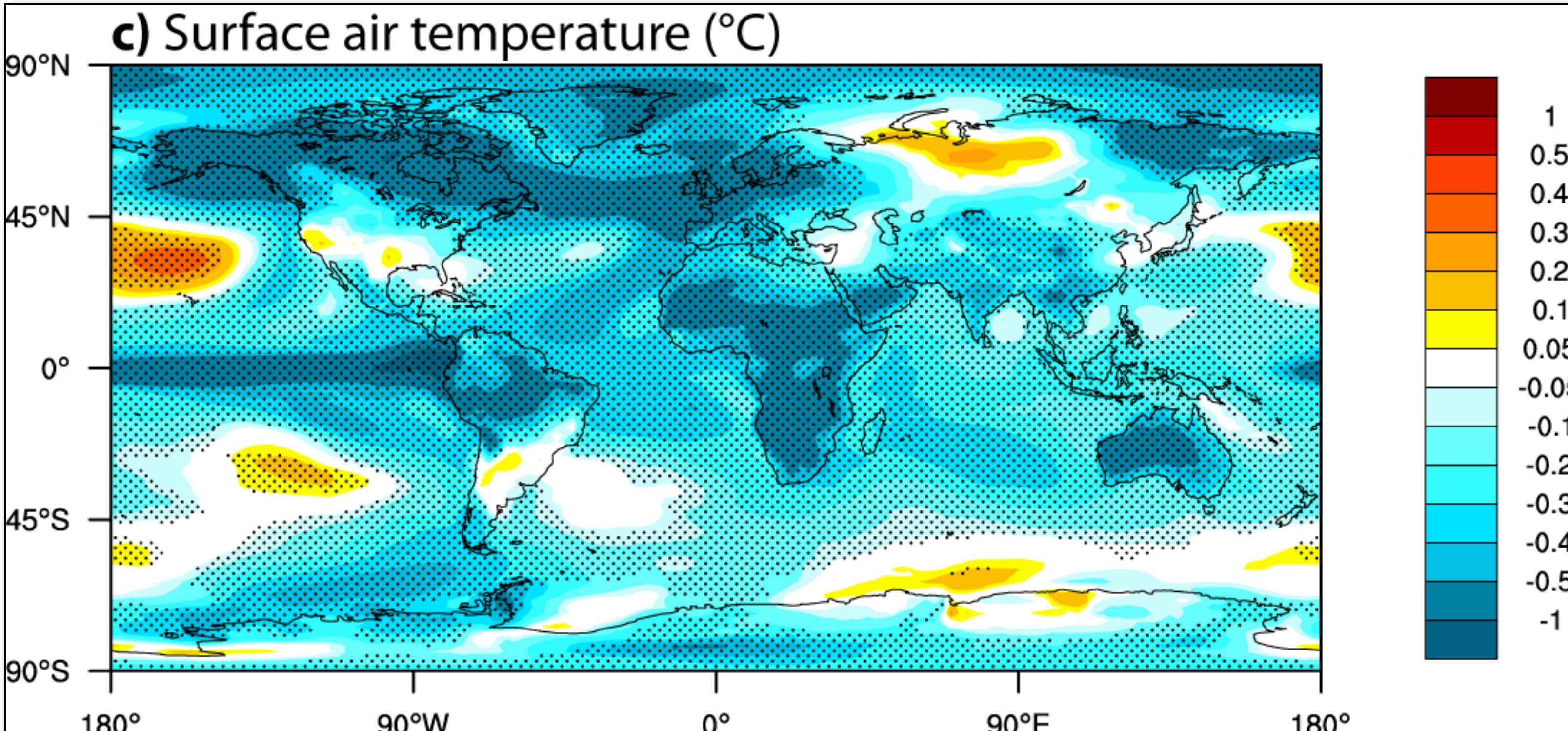
➢ All-sky net surface radiation decreased 1% (1.7 W m^{-2})



from: Tosca et al., 2012

Surface temperature response

➢ Surface temperature declined 0.3°C



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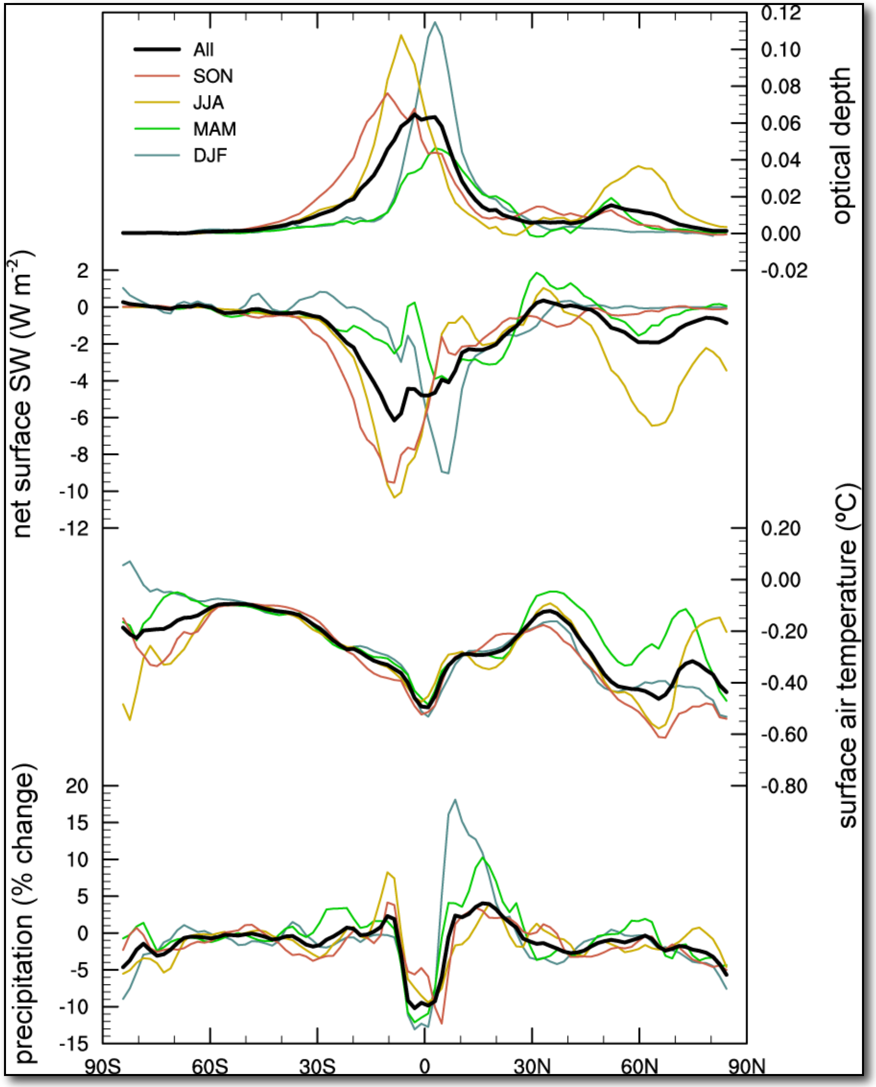
➢ Climate response to smoke aerosols *globally*

Zonal climate response

- ➢ Largest response near the equator
- ➢ Optical depth peaked near 5°N during DJF and 5°S during JJA
- ➢ Major reduction in precip near the equator during all seasons



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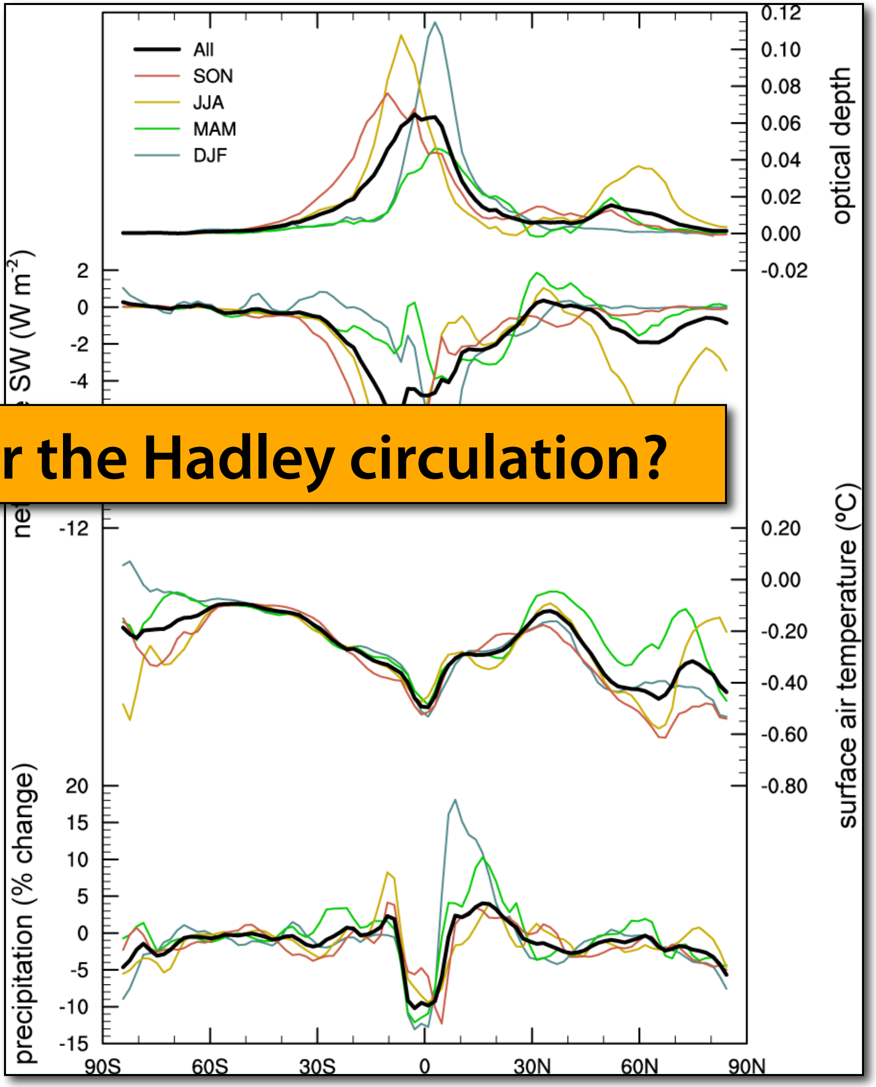
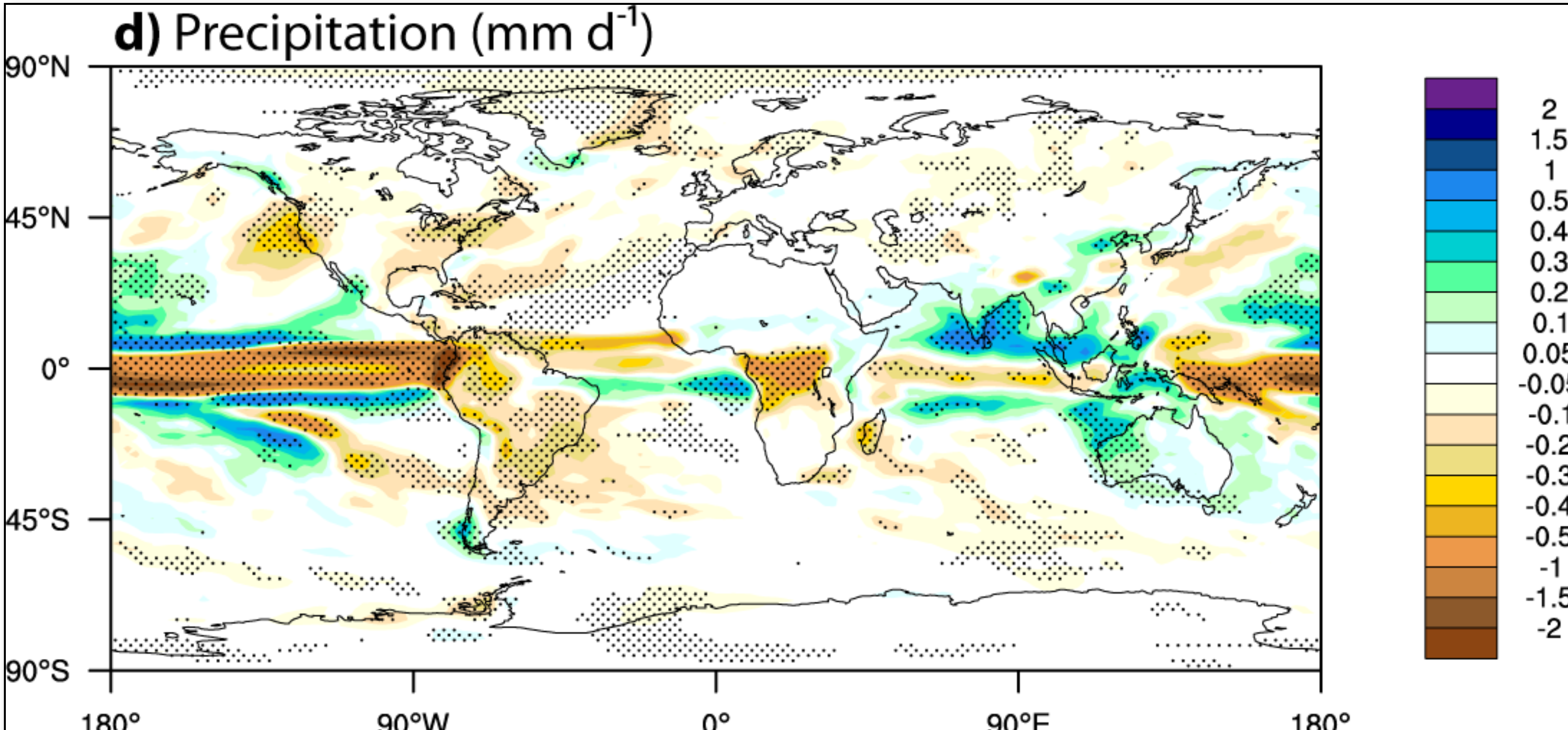


… do fire aerosols alter the Hadley circulation?

from: Tosca et al., 2012

Precipitation response - circulation changes?



➢ Though precipitation declined globally, there were large decreases at the equator, countered by slight increases to the north and south.

➢ Reductions over tropical forests = fires may increase their vulnerability to climate change

from: Tosca et al., 2012

Hadley Circulation changes

➢Diagnose Hadley Circulation using mass meriodional stream function (ψ),

$$\psi(\phi,p) = \frac{2\pi a\cos(\phi)}{g}\int_0^p [v(\phi,p)]dp$$

Which is equal to the rate at which mass is being transported meridionally (with positive values indicating northward transport) between that pressure level and the top of the atmosphere

from: Tosca et al., 2012

Hadley circulation changes, a summary

mid-troposphere heating from BC absorption

from: Tosca et al., 2012

Hadley circulation changes, a summary

mid-troposphere heating from BC absorption

+

surface cooling (especially in equatorial regions)

from: Tosca et al., 2012

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surface cooling (es

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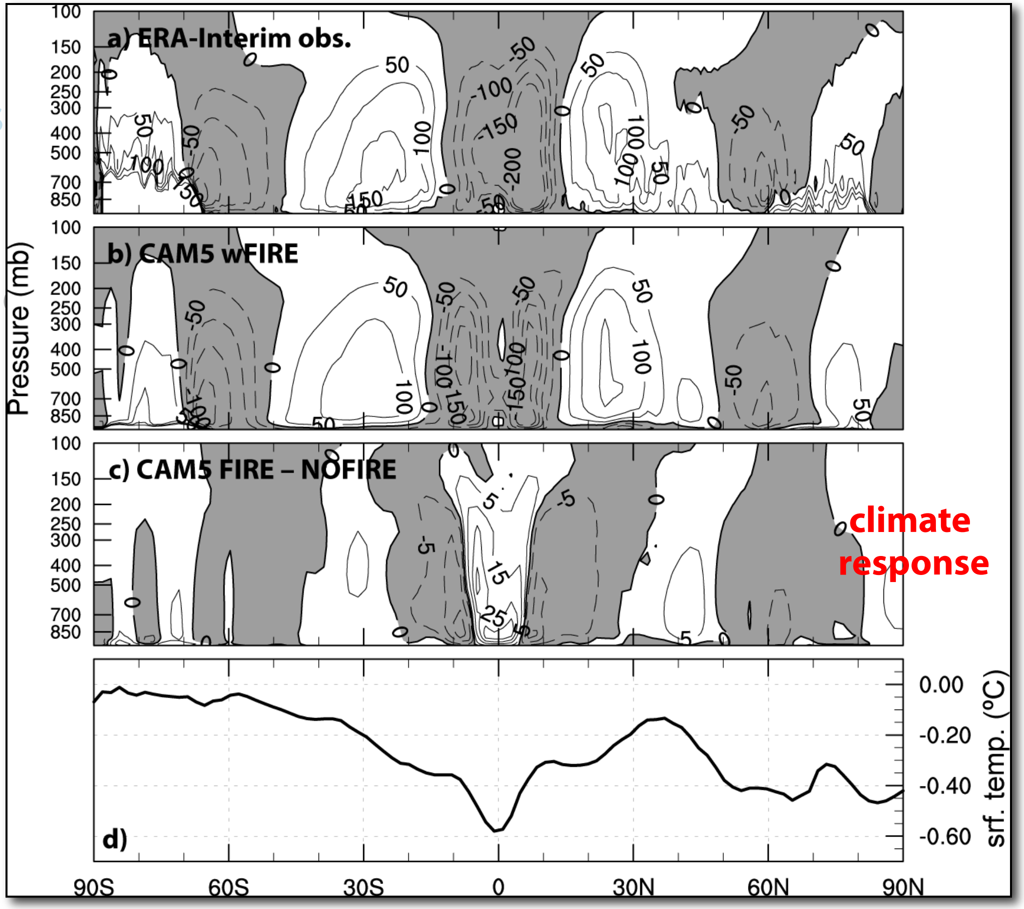


vertical velocity (ω)

shaded = upward velocities **(convection)**

unshaded = downward velocities **(subsidence)**

from: Tosca et al., 2012

Hadley circulation changes, a summary

mid-troposphere heating from BC absorption

+

surface cooling (especially in equatorial regions)

=

weakened equatorial convection

=

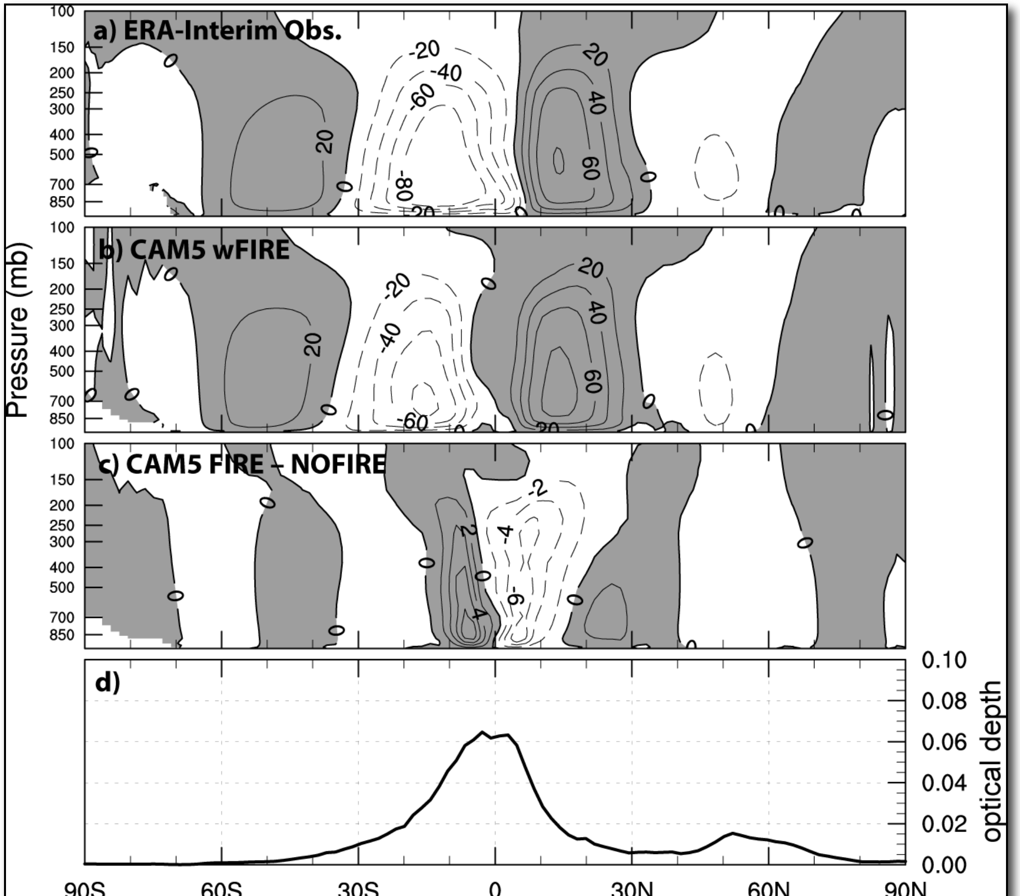
weaker Hadley circulation,

slight poleward expansion of descending branches

from: Tosca et al., 2012

Hadley circulation changes

Annually-averaged ψ



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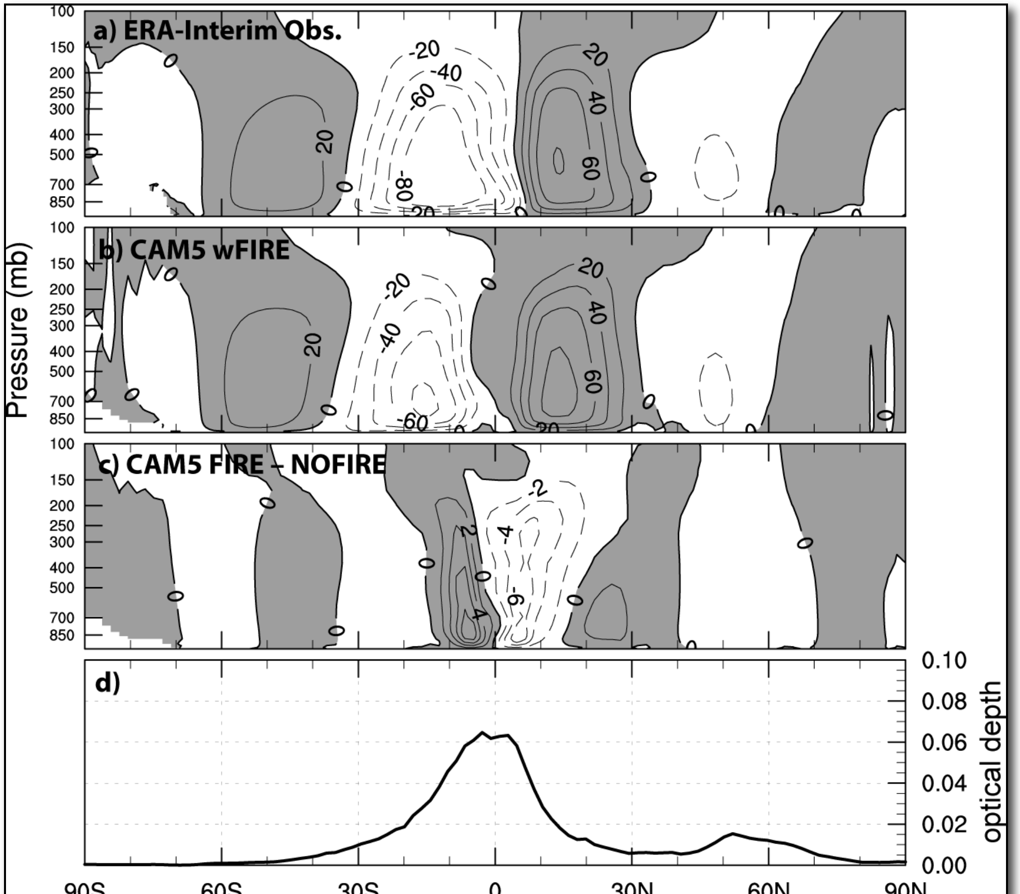

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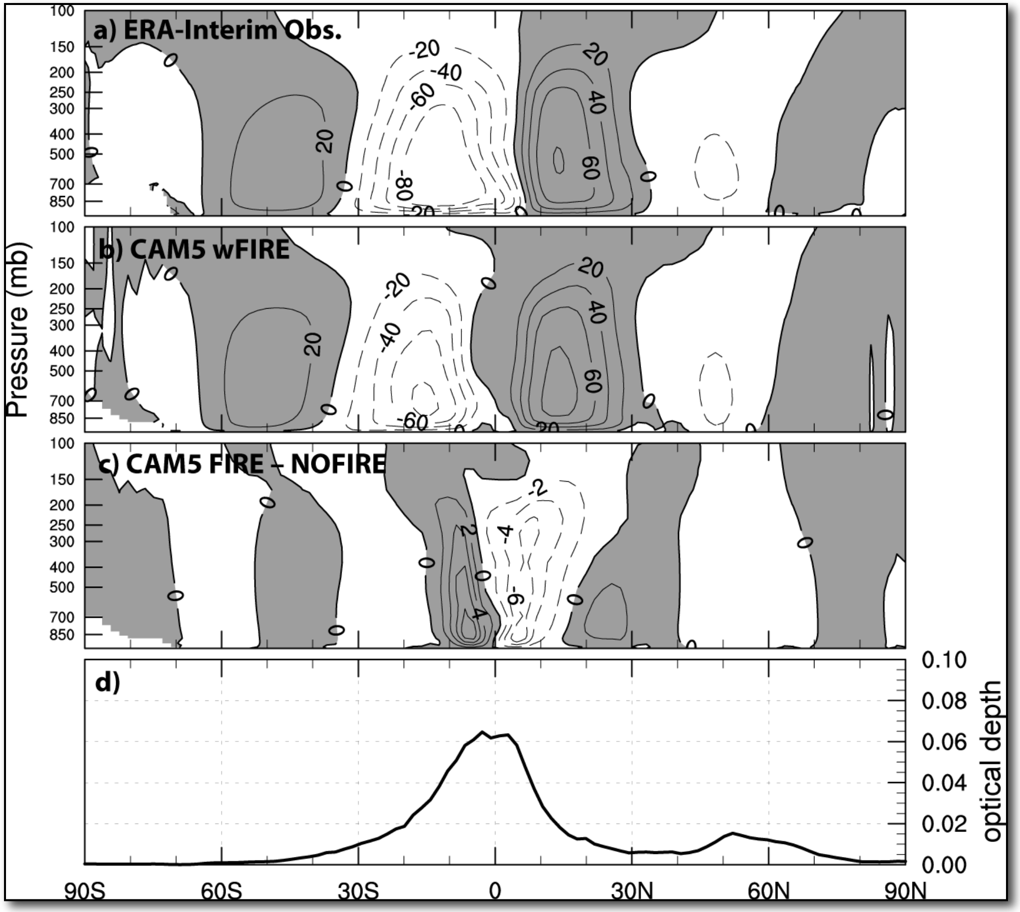
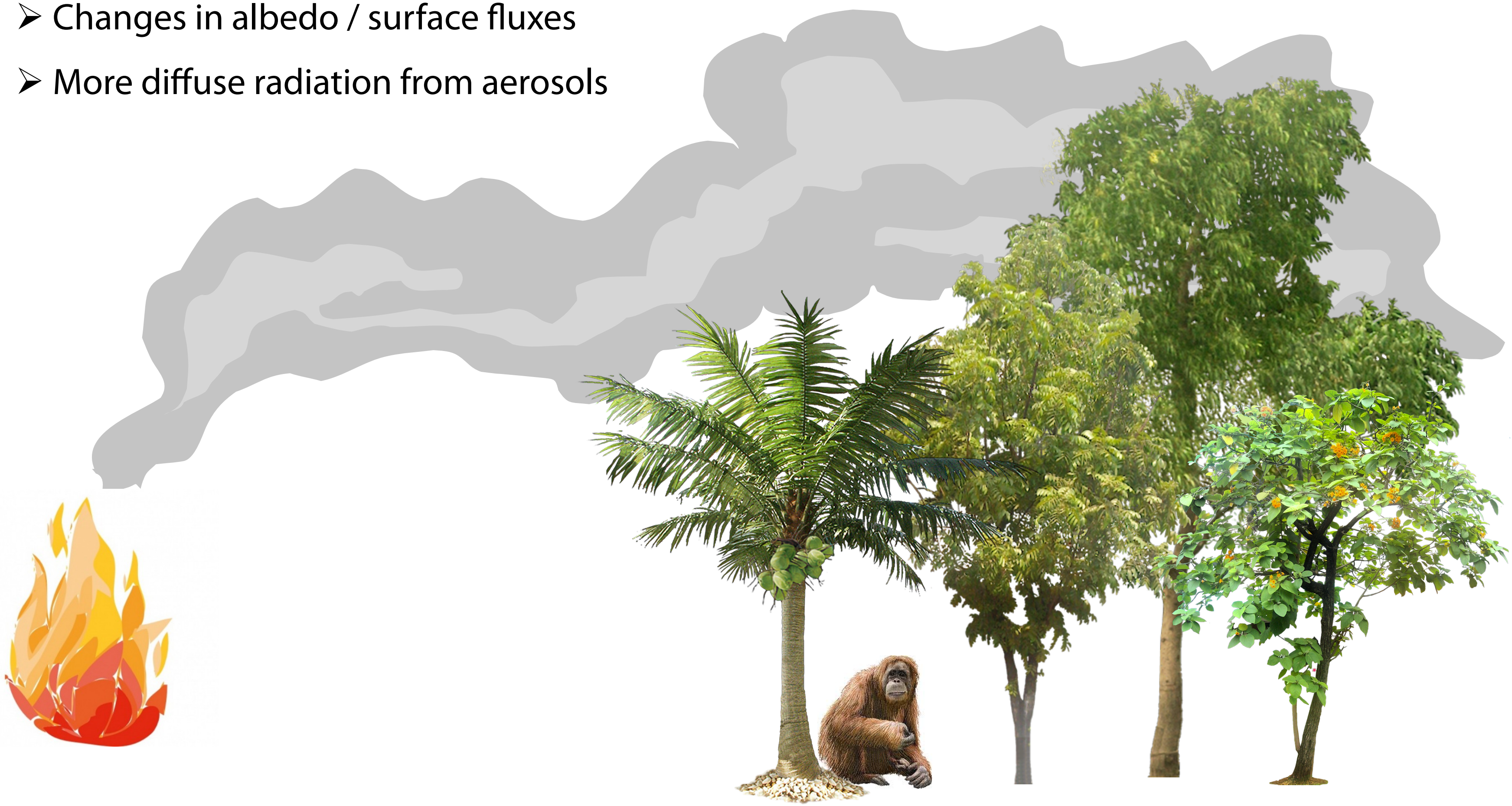


- ➢ Data from ECMWF matches well with output from CAM5
- ➢ Weaking of the streamfunction near the equator - in regions of highest AOD.
- ➢ Slight expansion of the Hadley cell – consistent with *Allen et al.*, (2012) and mid-latitude BC warming

from: Tosca et al., 2012

Total tropical forest ecosystem response to fire aerosols

- Climatic changes (precipitation, temperature)
- Direct deposition of nutrients (from aerosols) on ecosystems
- Changes in albedo / surface fluxes
- More diffuse radiation from aerosols



List of published manuscripts

Tosca, M. G., J. T. Randerson, C. S. Zender, M. G. Flanner and P. J. Rasch (2010), Do biomass burning aerosols intensify drought in equatorial Asia during El Niño?, *Atmos. Chem. Phys., 10*, 3515-3528, doi: 10.5194/acp-10-4515-2010.

Tosca, M. G., J. T. Randerson, C. S. Zender, D. L. Nelson, D. J. Diner and J. A. Logan (2011), Dynamics of fire plumes and smoke clouds associated with peat and deforestation fires in Indonesia, *J. Geophys. Res., 116*, D08207, doi: 10.1029/2010JD015148.

Zender, C. S., A. G. Krolewski, **M. G. Tosca** and J. T. Randerson (2011), Shape, reflectance, and age of smoke plumes from tropical biomass burning based on 2001-2009 MISR imagery, *in review, Atmos. Chem. Phys.*

Tosca, M. G., J. T. Randerson and C. S. Zender (2012), Global impacts of contemporary smoke aerosols from landscape fires on climate and the Hadley circulation, *submitted to Atmos. Chem. Phys.*

In conclusion

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(5) **Reduced equatorial convection (from surface cooling, atmospheric heating, indirect effects) weakens the Hadley circulation; mid-tropospheric BC warming increases tropical width**

Many thanks to…

Committee Chairs: Dr. Randerson & Dr. Zender

Committee Member: Dr. Yu

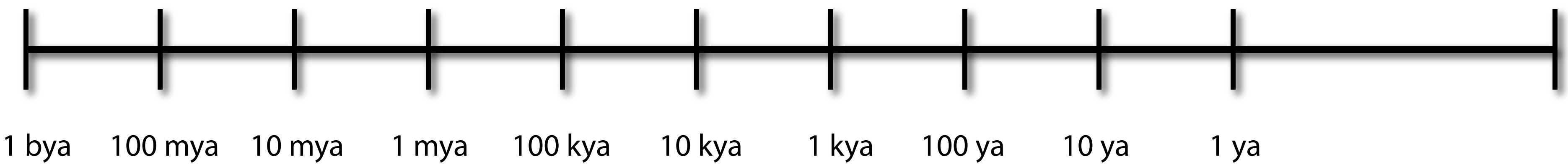
Co-authors: Mark Flanner (UMich), Dave Diner (JPL), Dave Nelson (JPL), Phil Rasch (PNNL), Jennifer Logan (Harvard)

Scott Capps (UCLA), Daniel Wang (SLAC), Guido van der Werf, Brendan Rogers, Claudia Pasquero, The Zender Group, The Randerson Group

UCI ESS staff, faculty and students…

Grateful for a NASA Earth Science Fellowship (NNX08AU90H)

A brief history of fire



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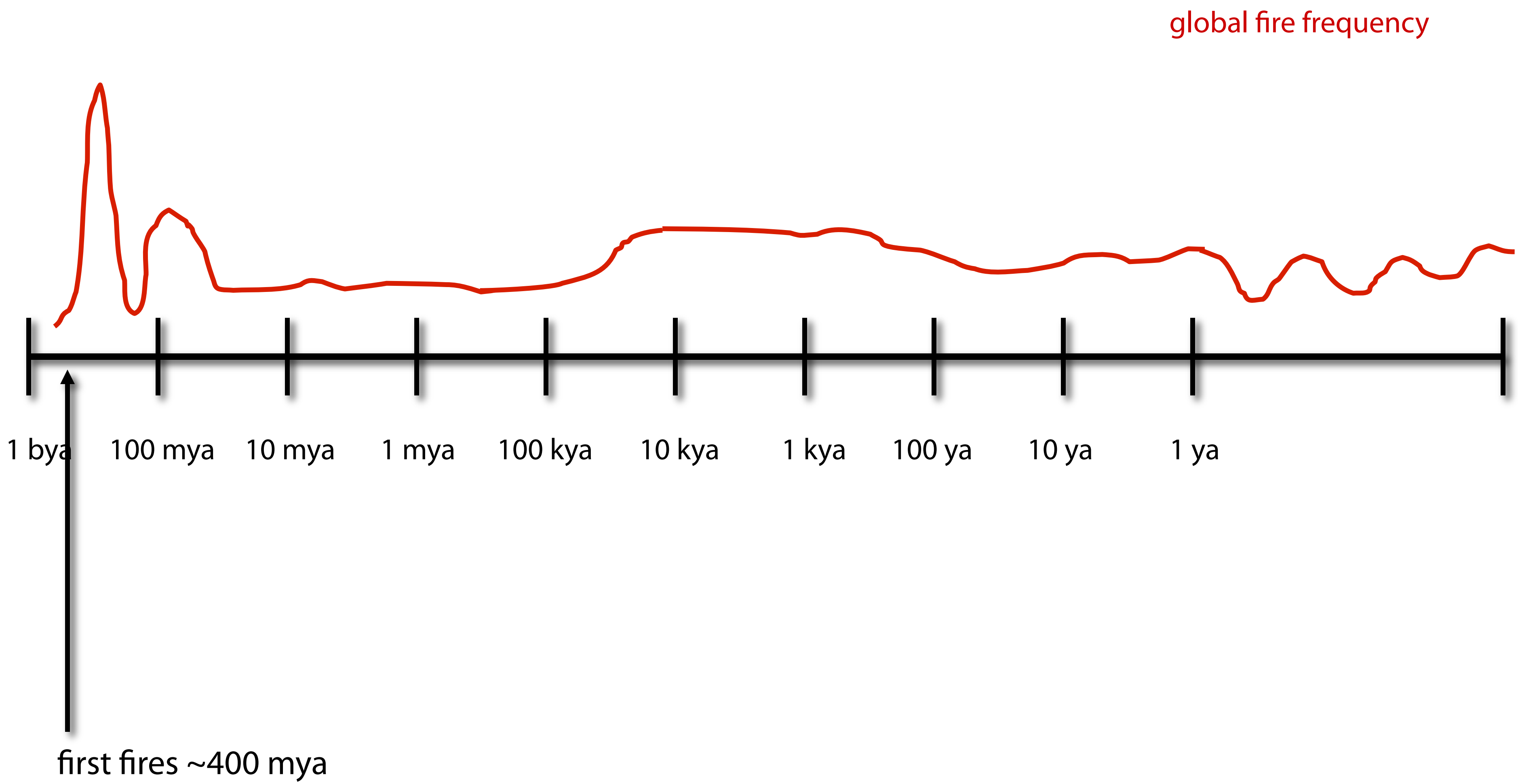

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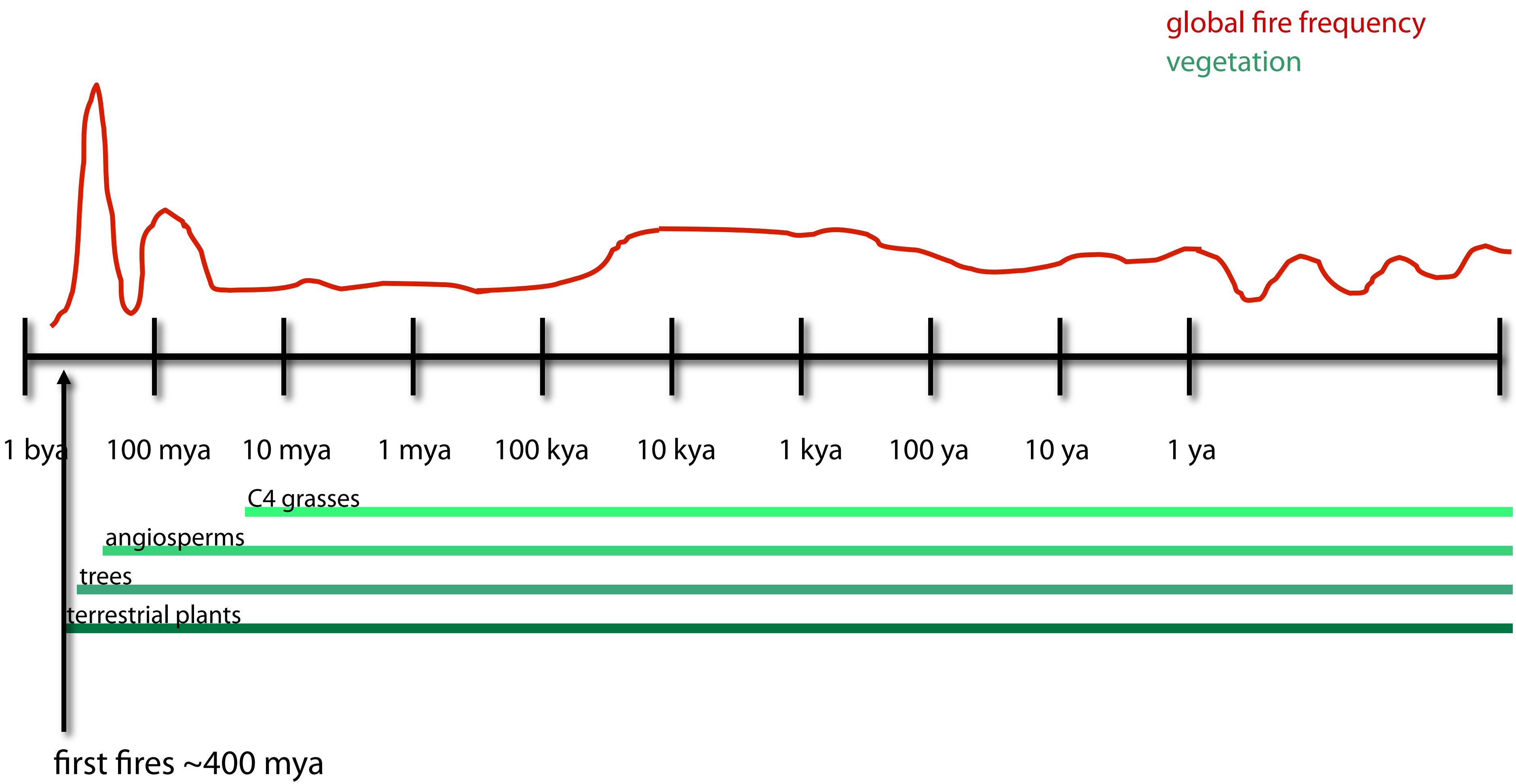

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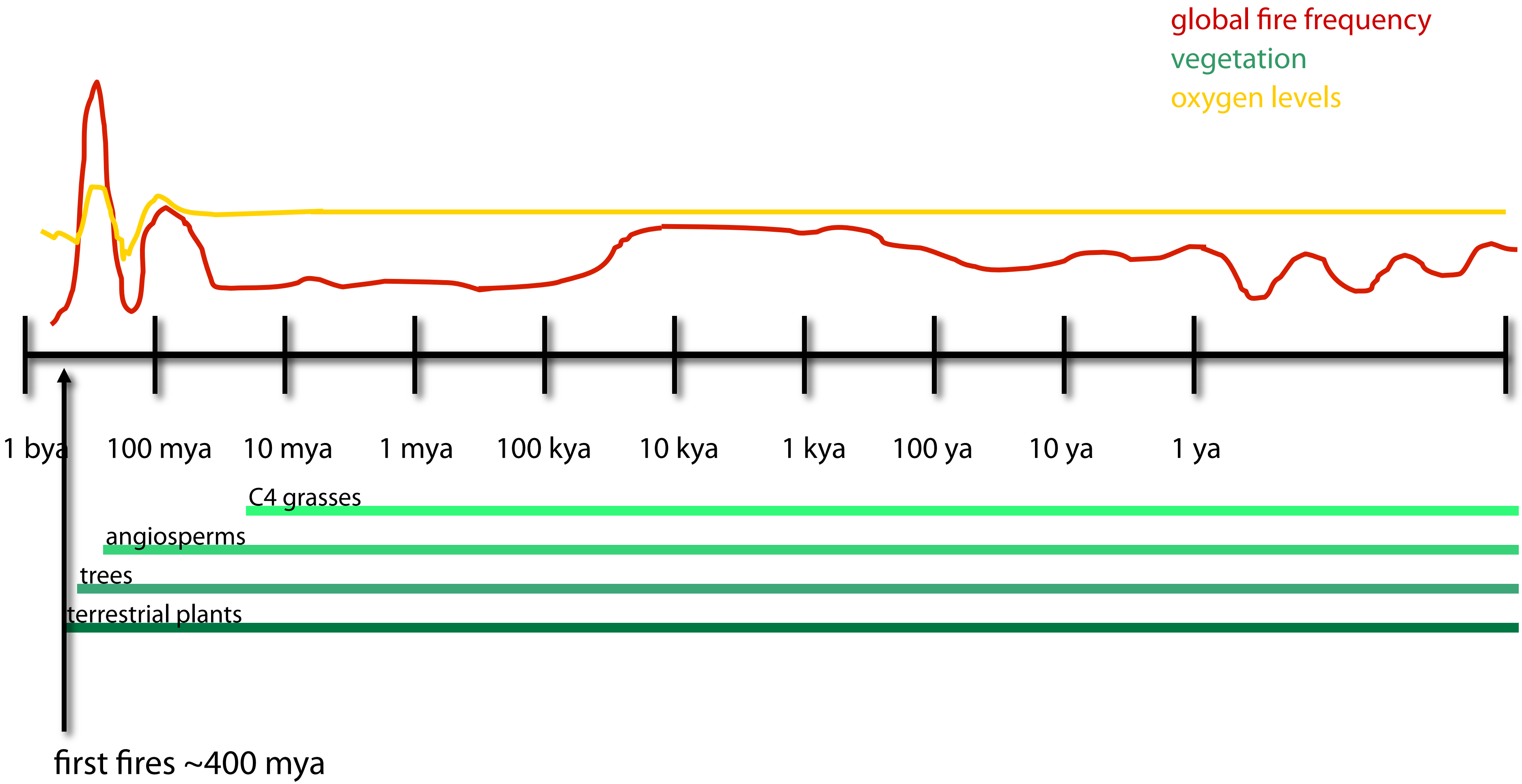

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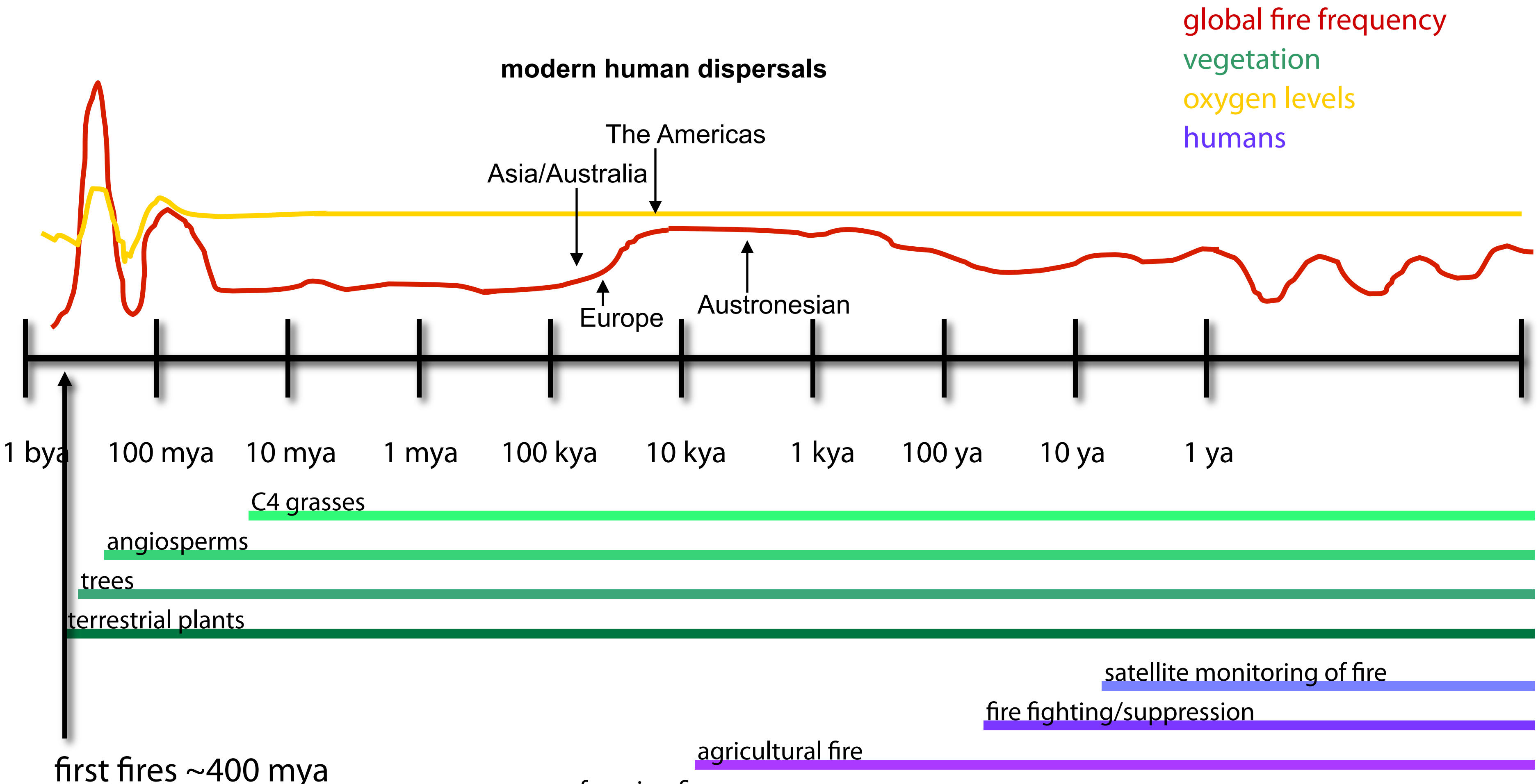

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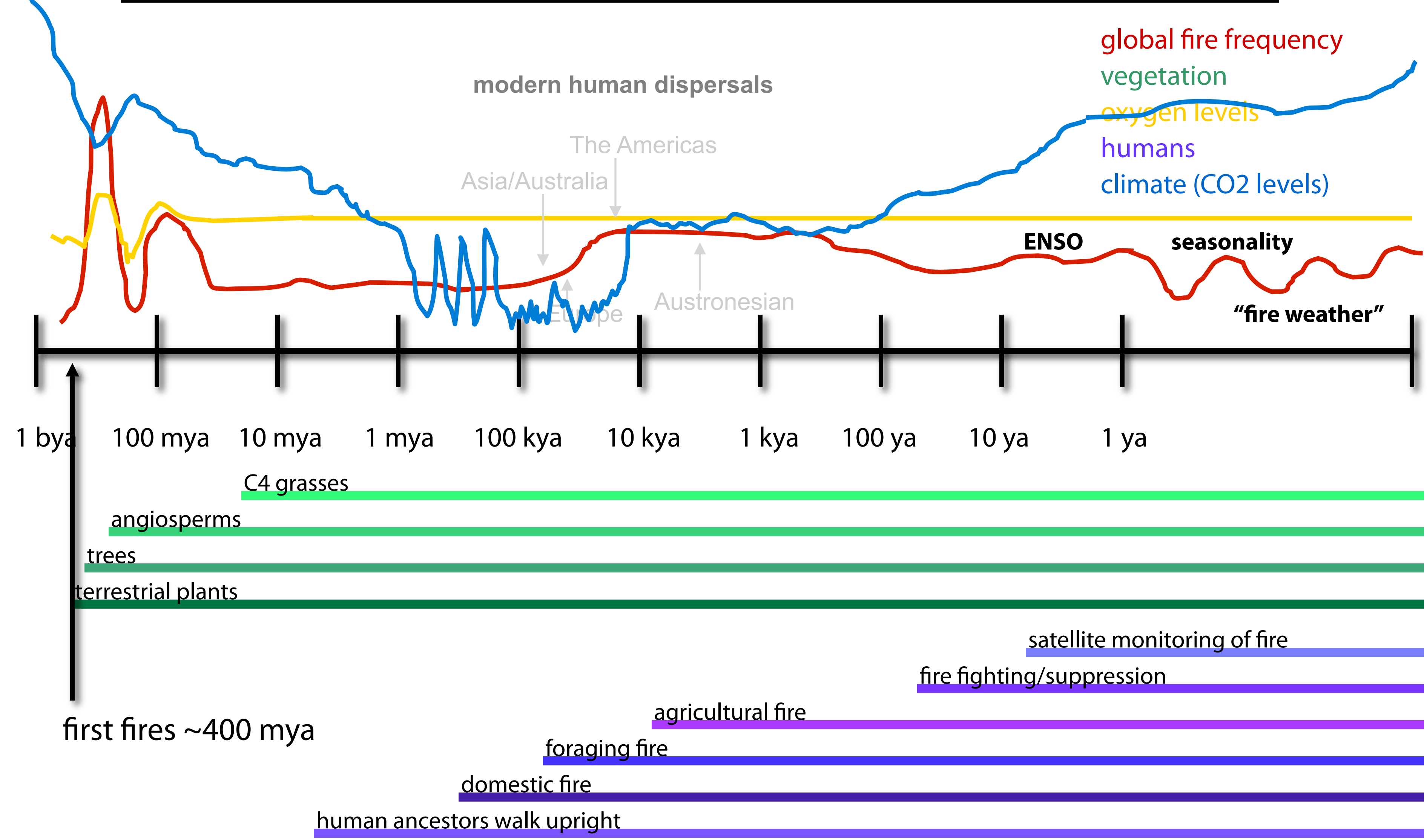
➢ 400 million years of fire on Earth

A brief history of fire



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